

X Marks the What?

{ Searching for exotic charmonium-like states at D0



Mark Williams
Fermilab Joint Theoretical-Experimental Seminar
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INDIANA UNIVERSITY

Mesons, Baryons, and Beyond?

1964: Gell-Mann & Zweig postulate Constituent Quark Model (CQM) –

- Explained all known mesonic and baryonic states
- Predicted others that were subsequently confirmed experimentally

CQM \Rightarrow Quarks form two types of bound states:

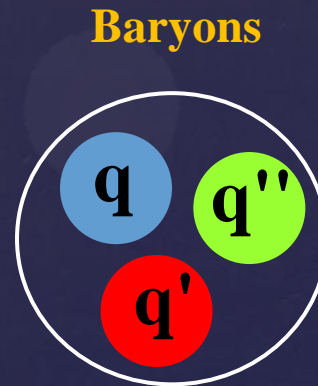
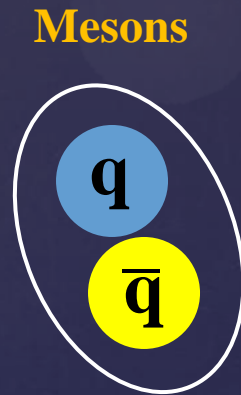


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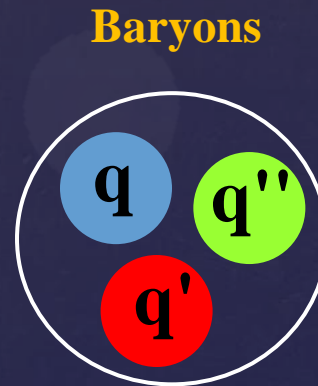
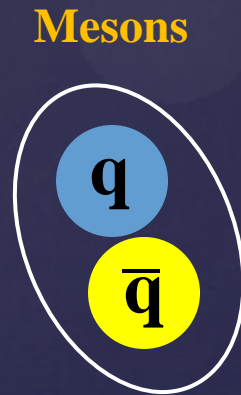
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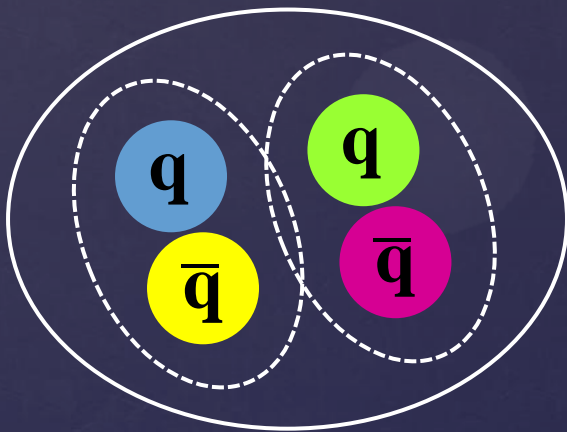
What about other combinations in bound states?

Mesons, Baryons, and Beyond?

No theoretical reason to exclude other types of (colorless) bound quark state

e.g.

Meson molecule



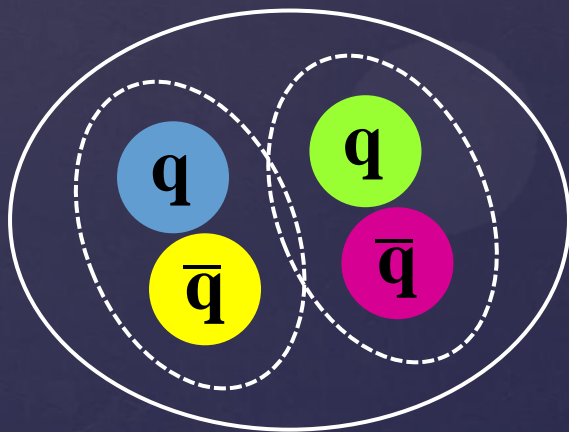
- Loosely bound
- Pion exchange @ large distances
- Some color exchange @ short distances
- Predicted to decay like pair of free mesons

Mesons, Baryons, and Beyond?

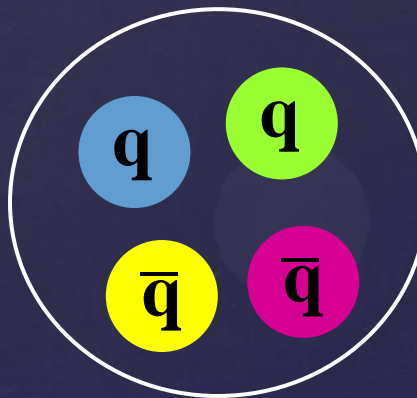
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Tetraquark



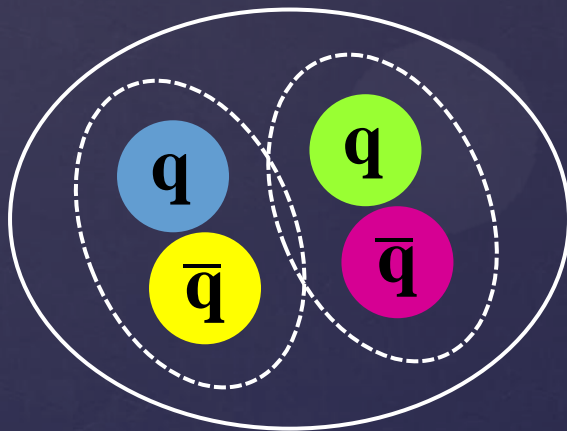
- Tightly bound
- Some models group into diquark-antidiquark pairs

Mesons, Baryons, and Beyond?

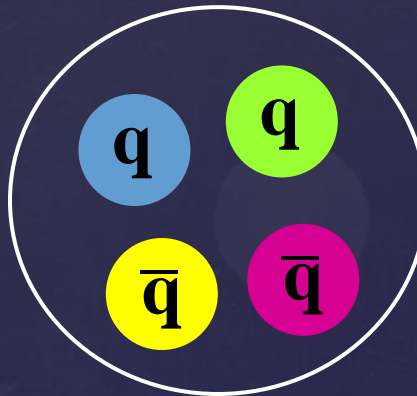
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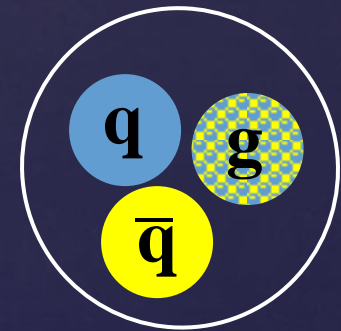
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Tetraquark



Quark-gluon hybrid



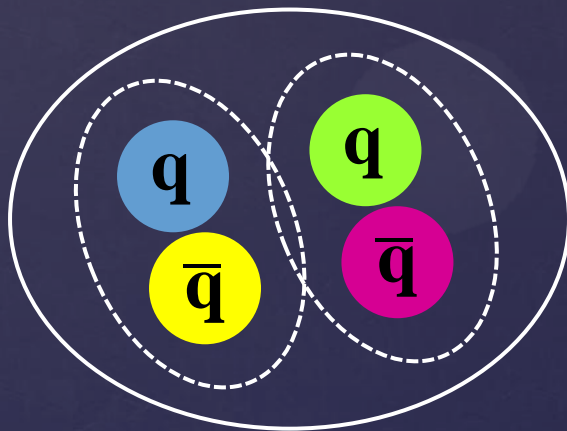
- Extra gluonic degree-of-freedom

Mesons, Baryons, and Beyond?

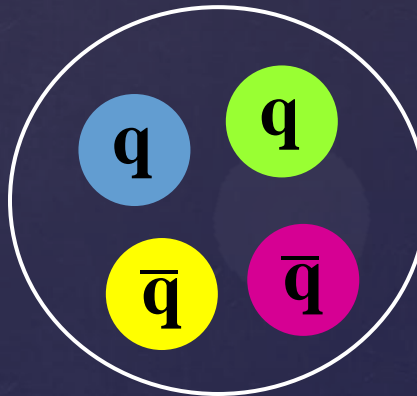
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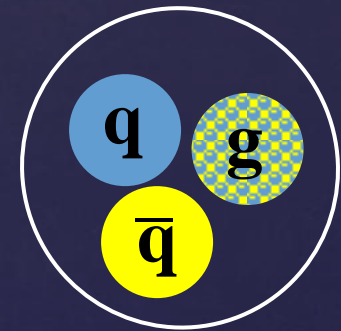
Meson molecule



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But... until recently, no definitive experimental evidence for any such states

Charmonium

Exotic multi-quark states have been long predicted in the light quark sector

e.g. $f_0(980)$ and $a_0(980)$ candidates for $K\bar{K}$ molecules

But... Difficult to differentiate from conventional states – 3 light quarks, isospin symmetry, broad resonances, dense spectrum of predicted mesons.

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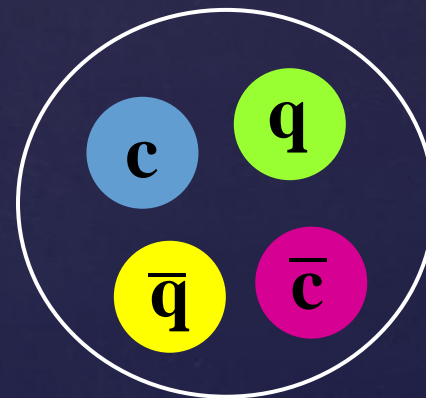
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But... Difficult to differentiate from conventional states – 3 light quarks, isospin symmetry, broad resonances, dense spectrum of predicted mesons.

Charmonium ($c\bar{c}$) states have well-predicted conventional spectrum, and distinct properties:

- Zero charge, zero strangeness
- Constrained decay channels
- Easier to differentiate from exotic states

Exotic charmonium states can be charged ($c\bar{c}u\bar{d}$), strange ($c\bar{c}d\bar{s}$) or both ($c\bar{c}u\bar{s}$)

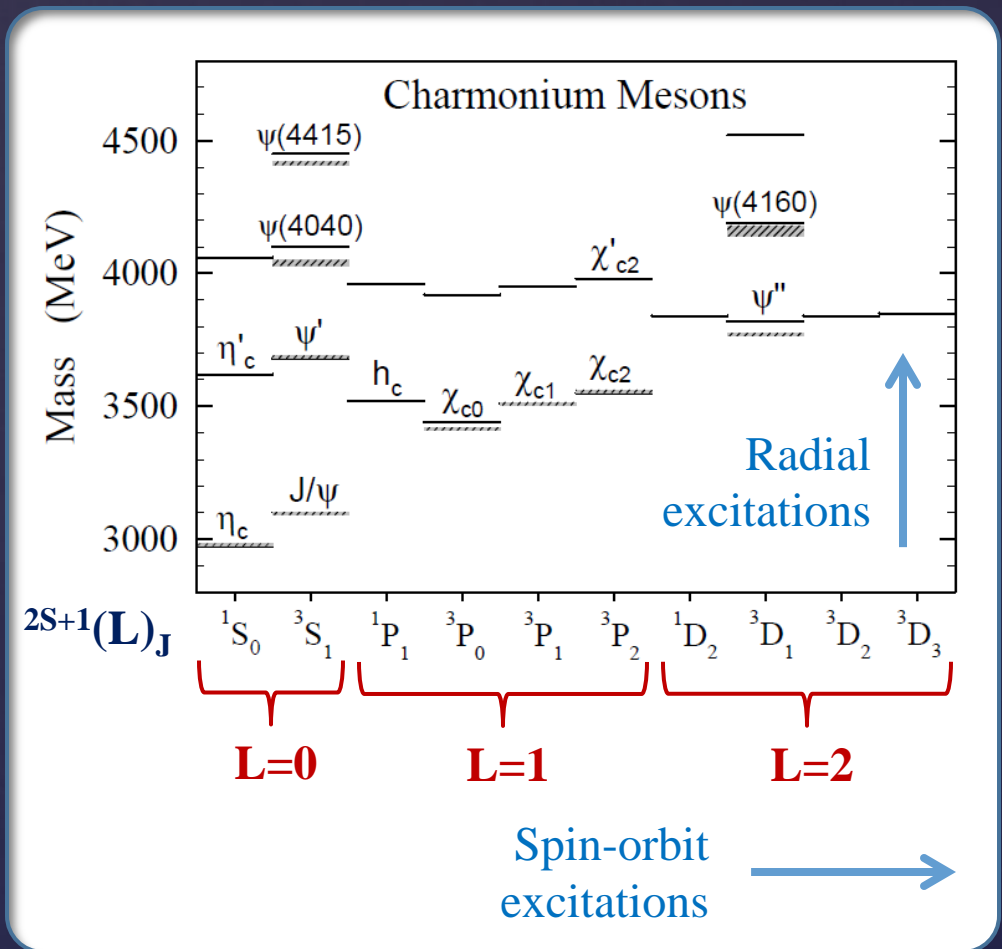


Charmonium

States defined by radial, spin, orbital, and total angular momentum quantum numbers

Spectrum well described by QCD quark-potential models

Later discoveries (η'_c , h_c , χ'_{c2}) agree with predictions



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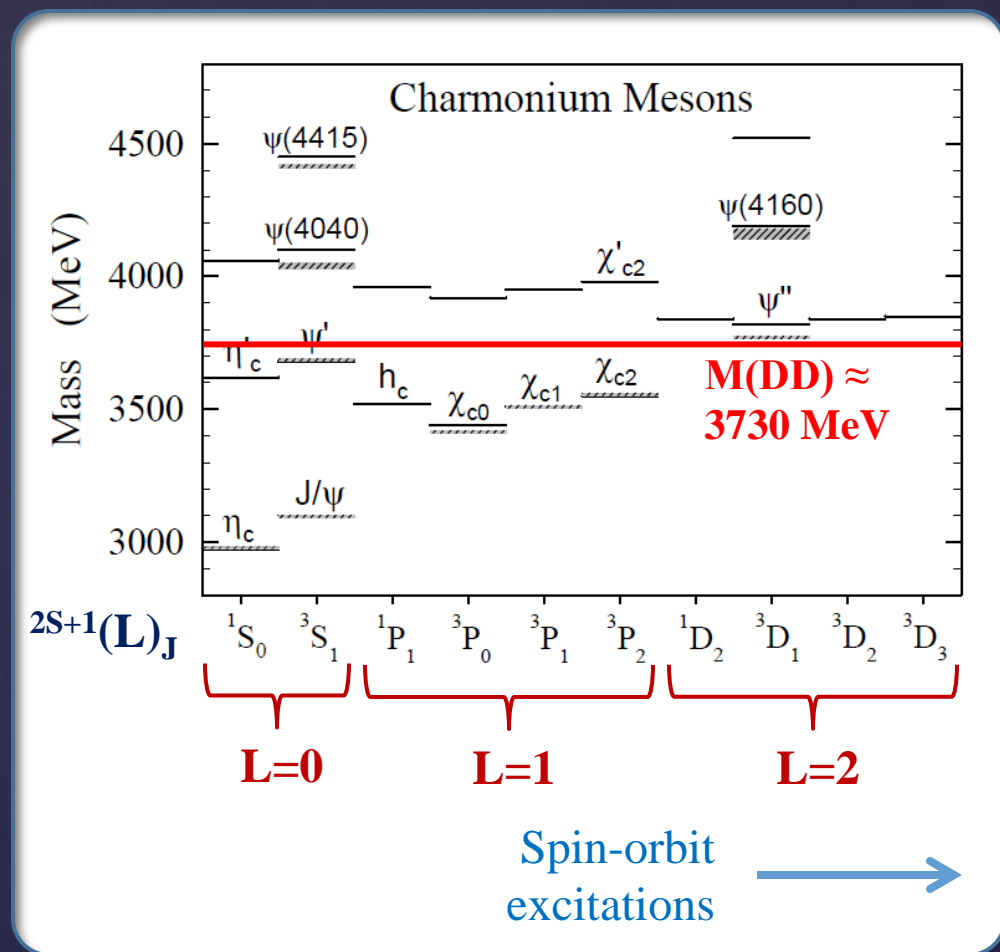
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‘Open charm’ thresholds important for $c\bar{c}$ decays (i.e. DD, DD^*, D^*D^*)

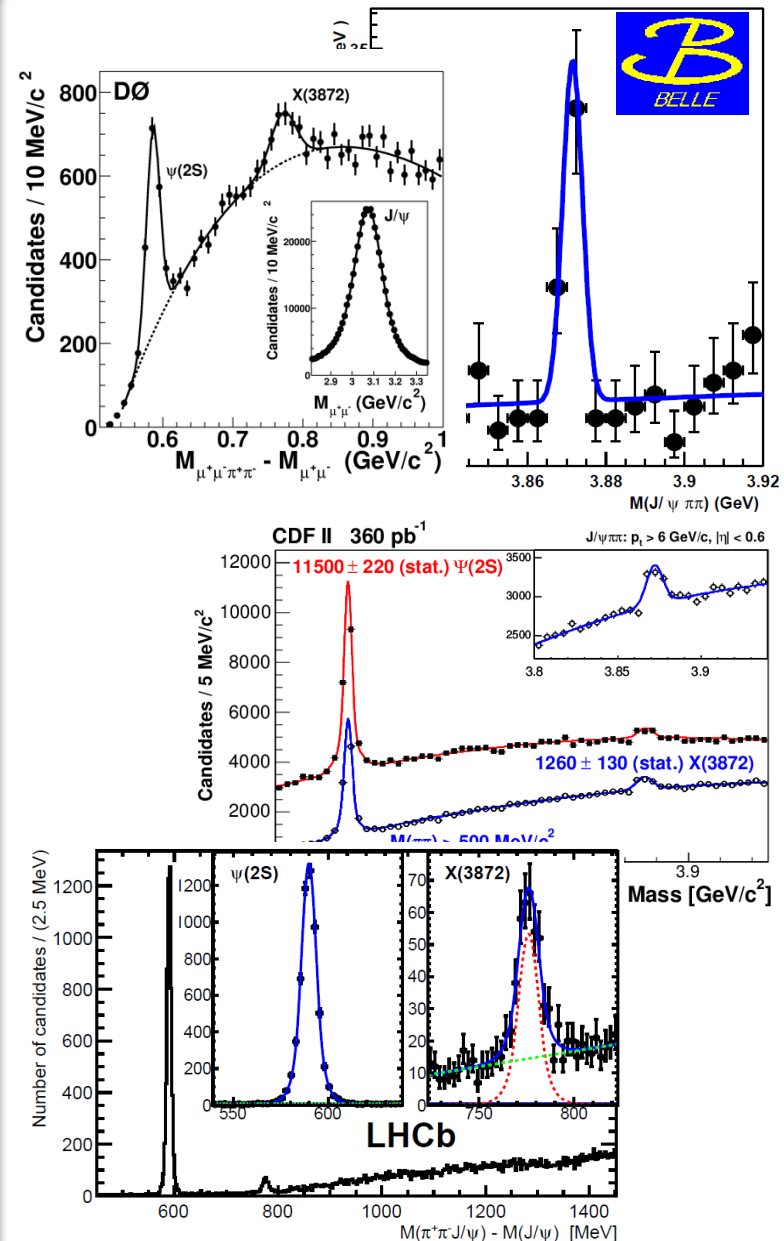
$\Rightarrow M(DD) \approx 3730$ MeV:
charmonium states above this mass decay mainly to DD pairs.



First Hint: X(3872)

$X(3872) \rightarrow J/\psi \pi^+ \pi^-$ observed by Belle in 2003 in decays $B^- \rightarrow X(3872) K^-$

Confirmed soon after by CDF, D0, BaBar



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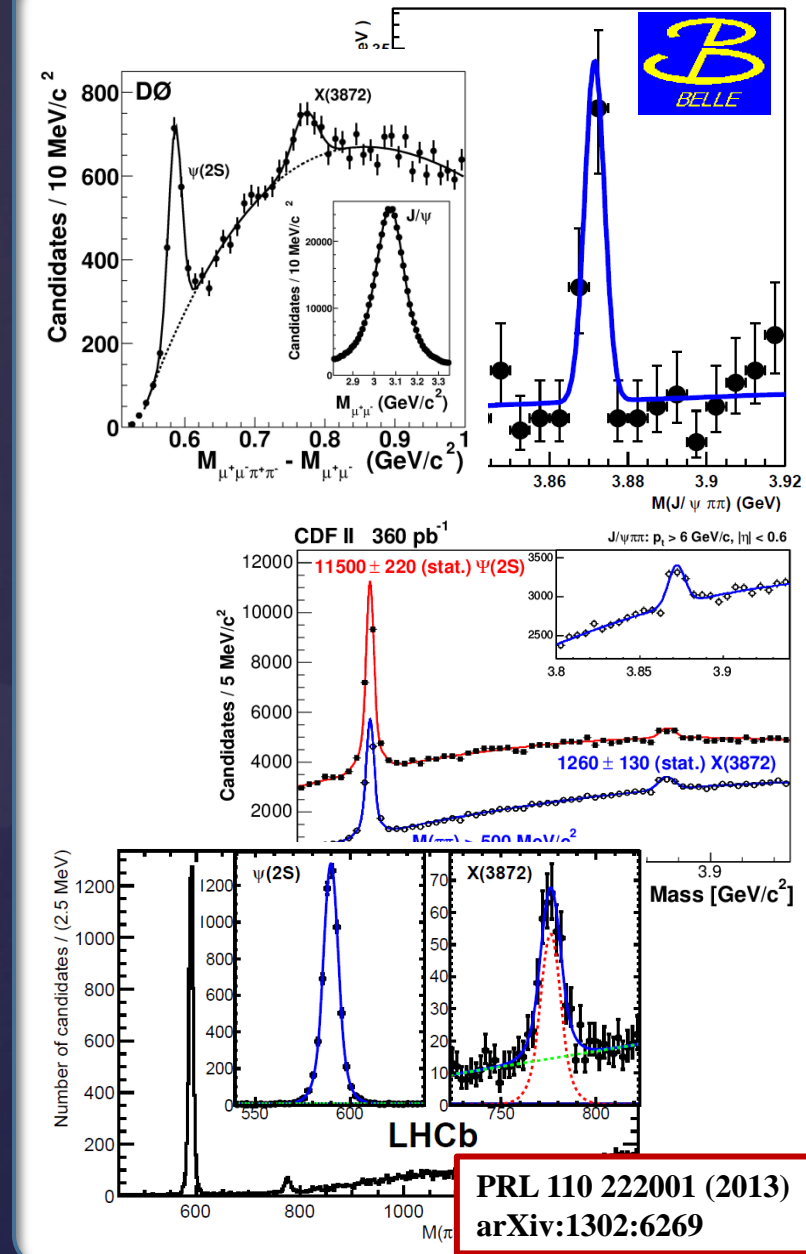
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Why can't this be conventional charmonium?

- 1) Detailed analysis implies dipion is from decay $\rho \rightarrow \pi\pi$, but $c\bar{c} \rightarrow \rho J/\psi$ violates isospin
- 2) Quantum numbers (determined by LHCb, 2013) are $J^{PC} = 1^{++}$, but neither of the corresponding charmonium states should decay to $J/\psi \pi\pi$

The X(3872) very close (≈ 1 MeV) to $D^0 \bar{D}^{*0}$ threshold \Rightarrow likely explanation is a meson molecule, with some $c\bar{c}$ component.

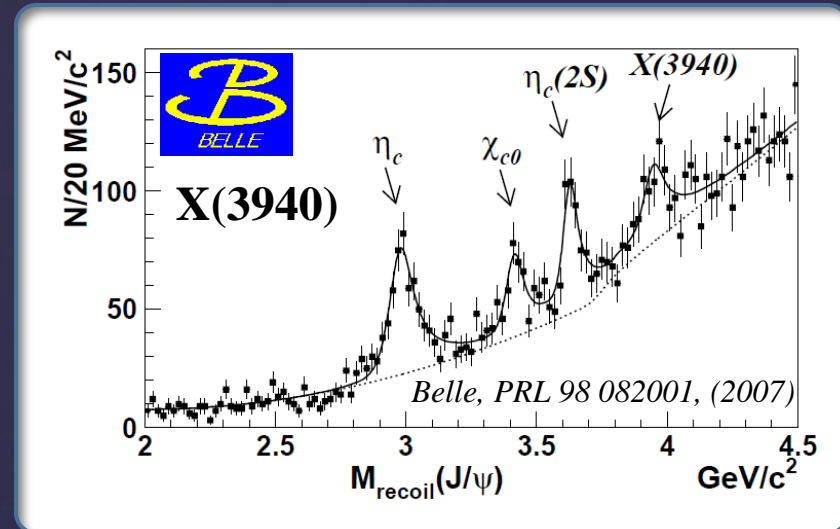
No charged equivalent ($D^\pm D^*$) has been observed



More Surprises

After the X(3872) discovery, many unexpected resonances observed, inconsistent with expected charmonium spectrum

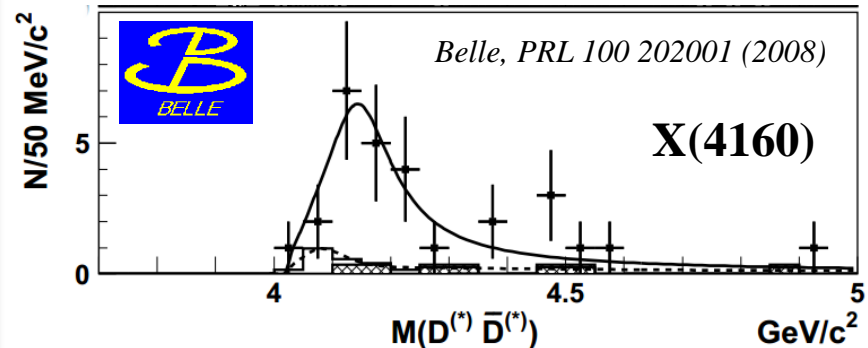
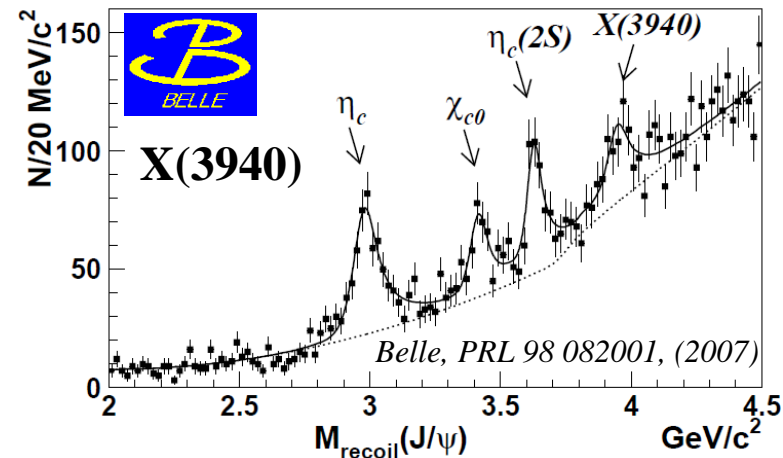
Some states subsequently adopted into existing $c\bar{c}$ scheme, others remain a mystery



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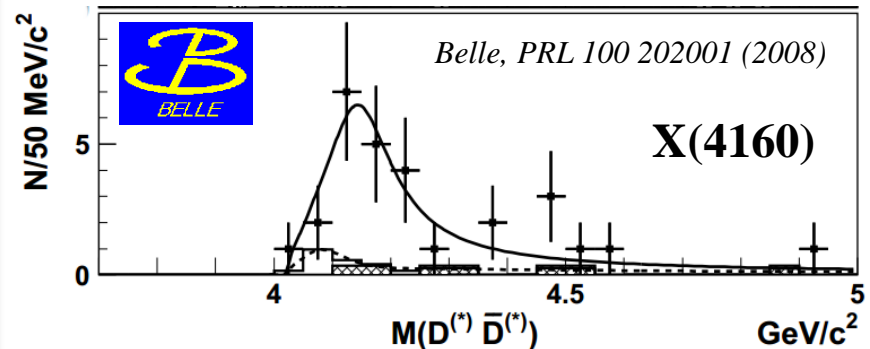
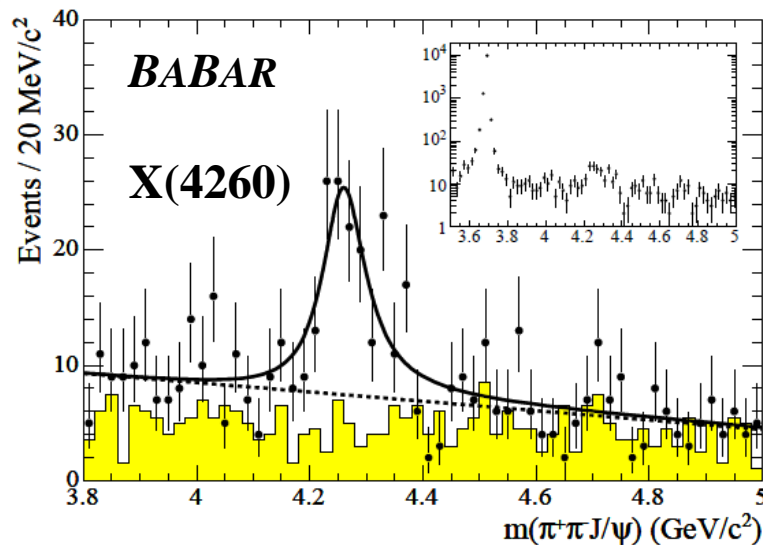
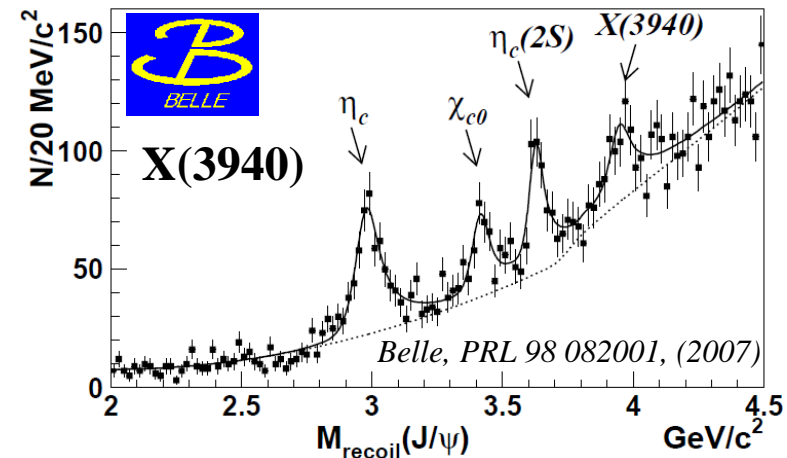
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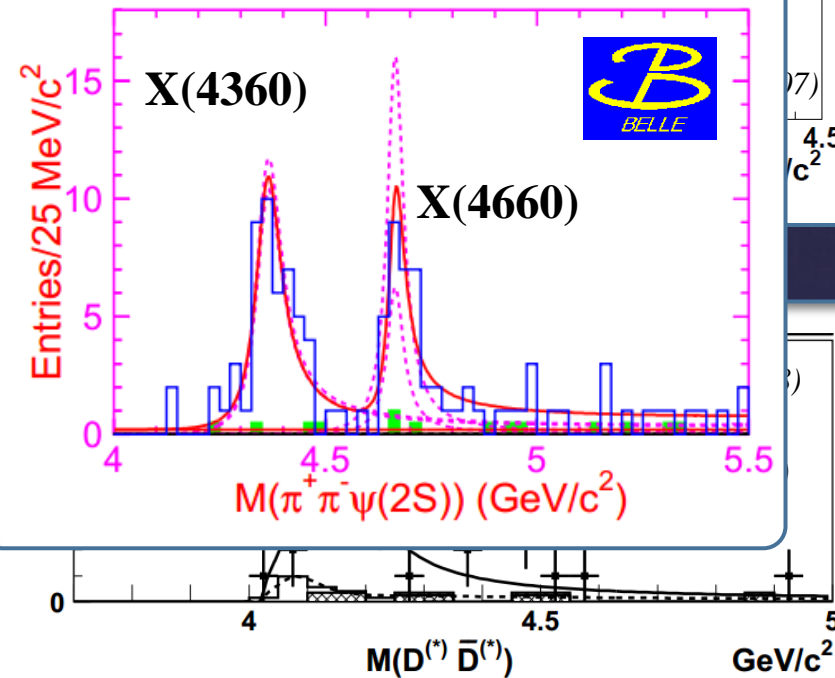
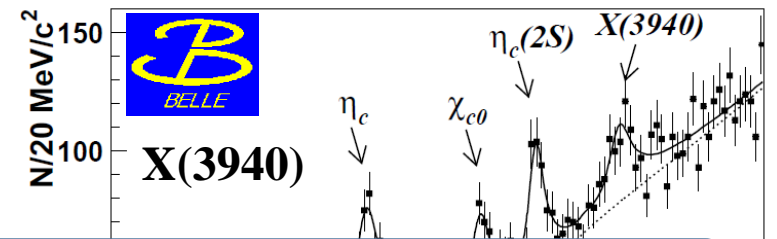
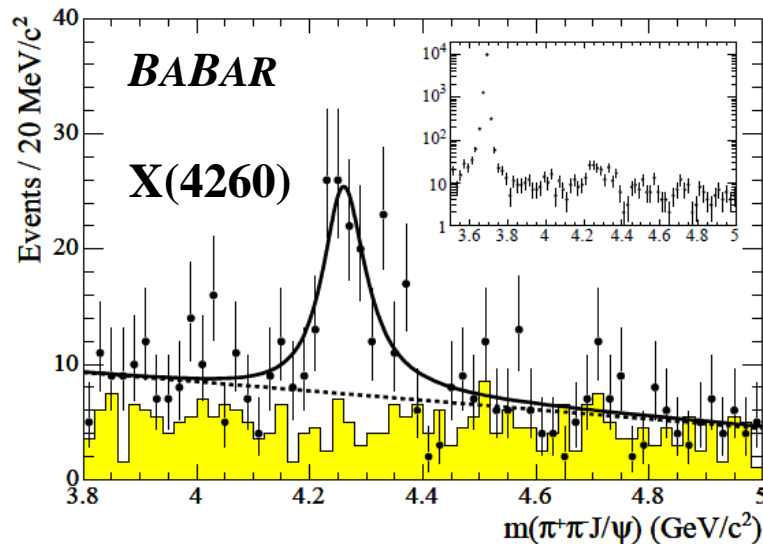
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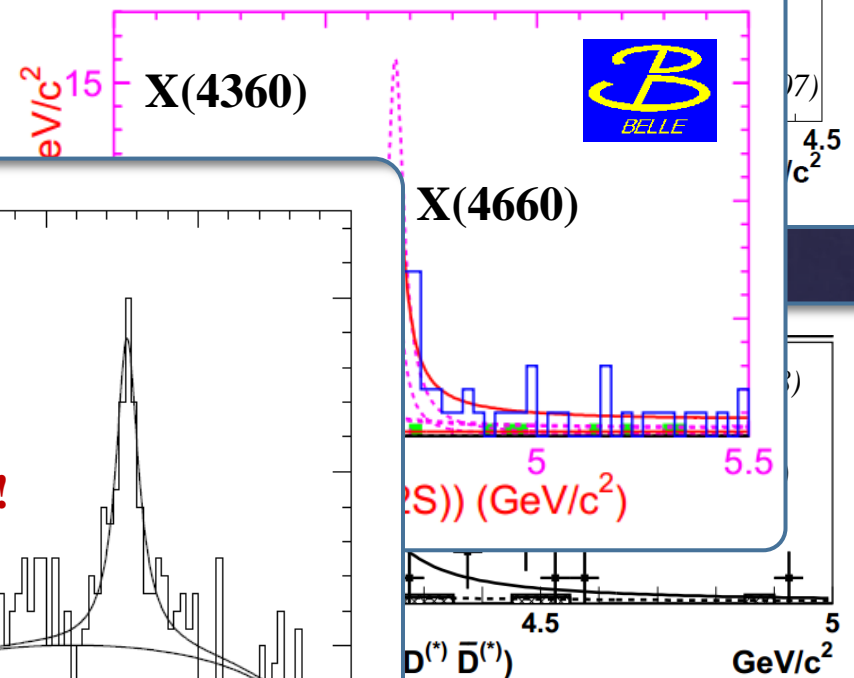
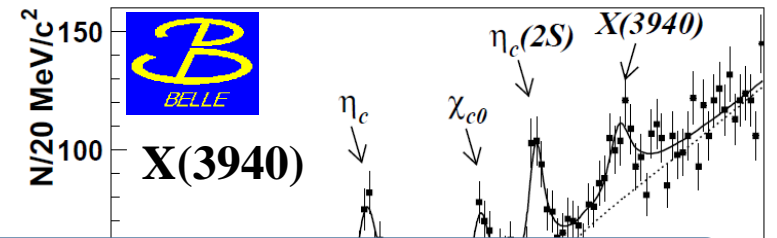
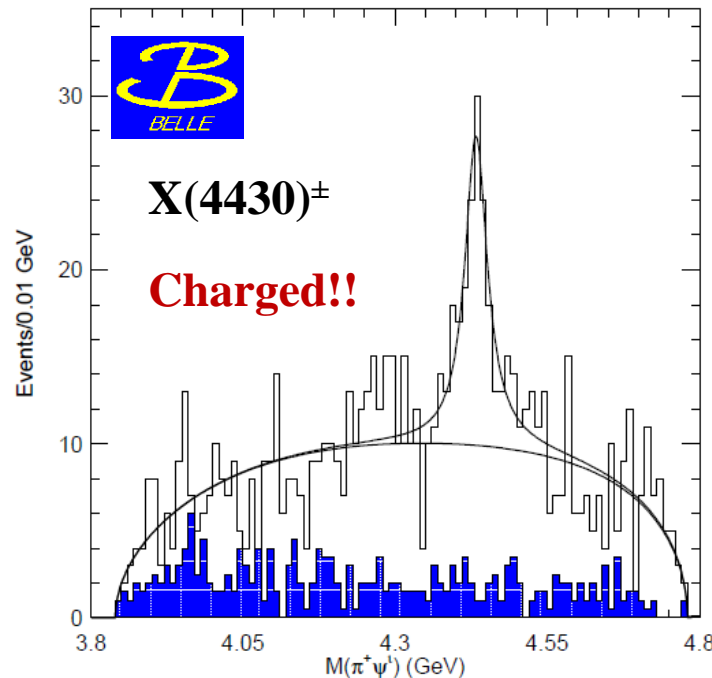
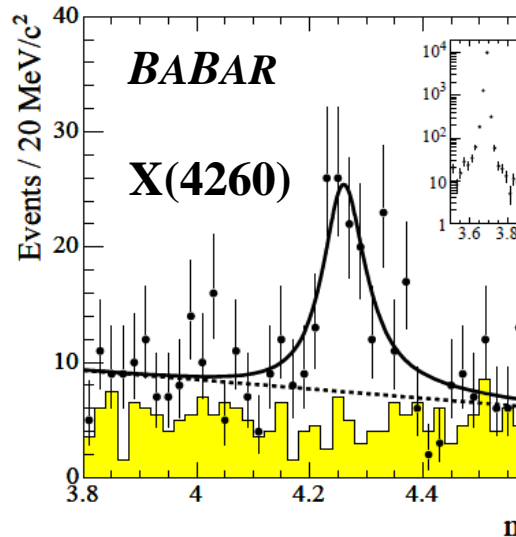
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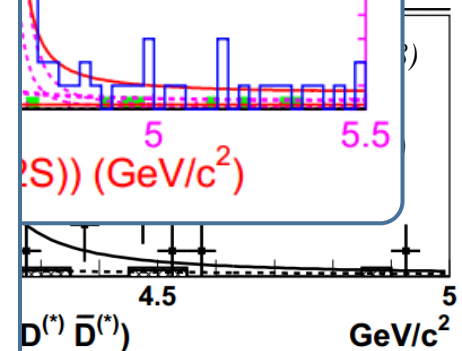
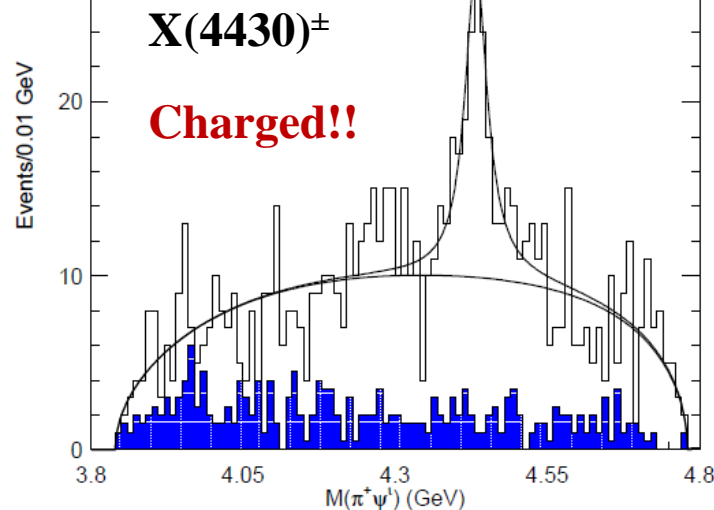
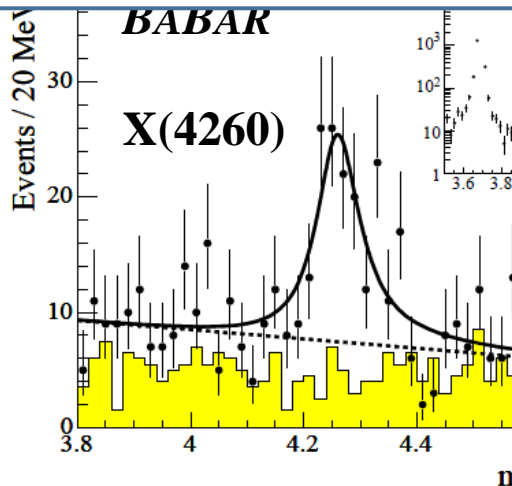
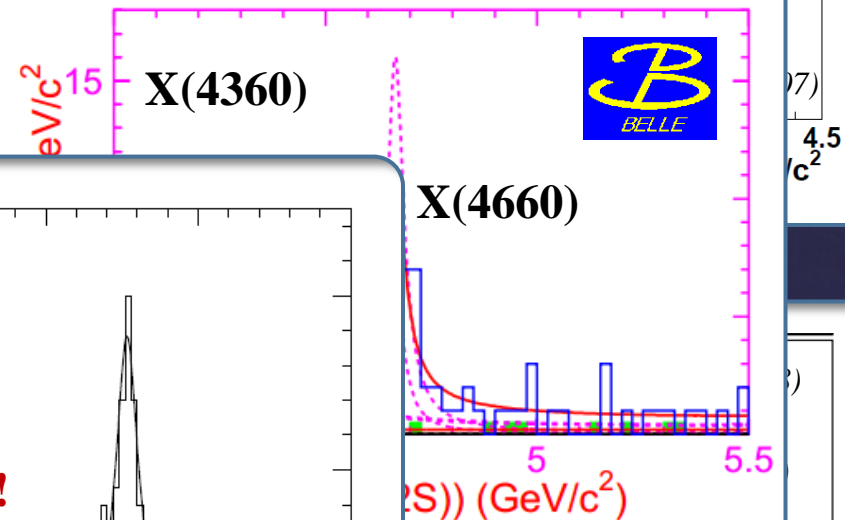
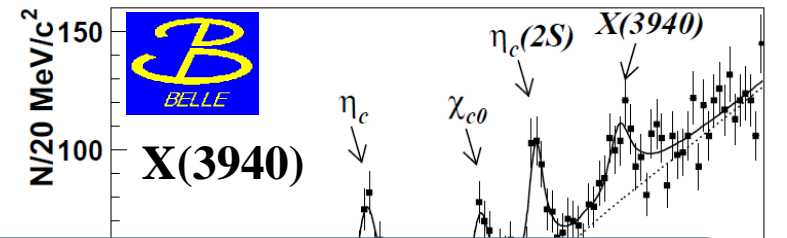
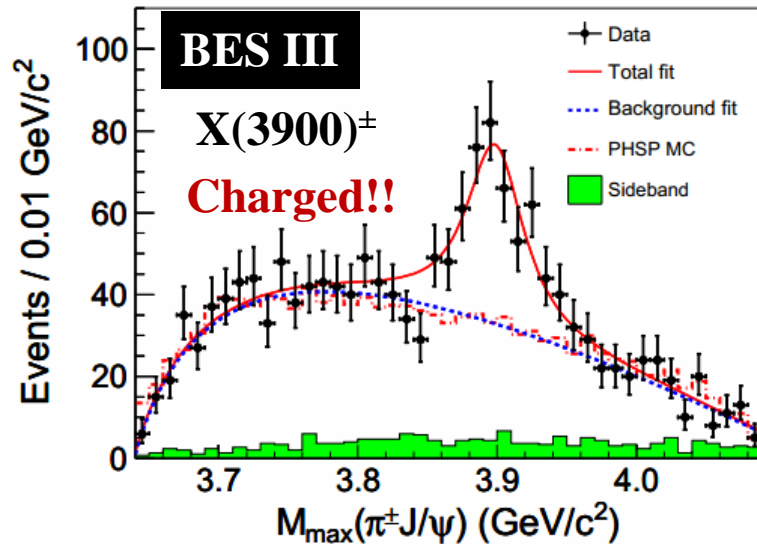
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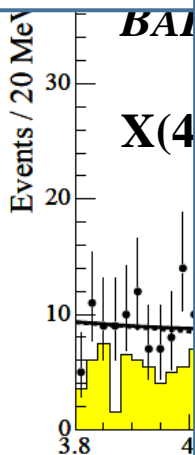
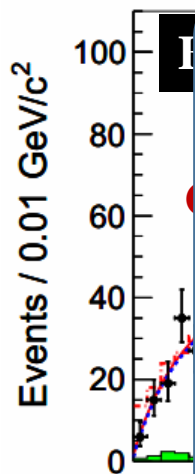
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State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\# \sigma$)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	$1^{++}/2^{-+}$	$B \rightarrow K(\pi^+\pi^-J/\psi)$	Belle [36, 37] (12.8), BABAR [38] (8.6)	2003	OK
				$p\bar{p} \rightarrow (\pi^+\pi^-J/\psi) + \dots$	CDF [39–41] (np), DØ [42] (5.2)		
				$B \rightarrow K(\omega J/\psi)$	Belle [43] (4.3), BABAR [23] (4.0)		
				$B \rightarrow K(D^{*0}\bar{D}^0)$	Belle [44, 45] (6.4), BABAR [46] (4.9)		
				$B \rightarrow K(\gamma J/\psi)$	Belle [47] (4.0), BABAR [48, 49] (3.6)		
				$B \rightarrow K(\gamma\psi(2S))$	BABAR [49] (3.5), Belle [47] (0.4)		
				$pp \rightarrow (\pi^+\pi^-J/\psi) + \dots$	LHCb [50] (np)		
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	$0/2^{2+}$	$B \rightarrow K(\omega J/\psi)$	Belle [51] (8.1), BABAR [52] (19)	2004	OK
				$e^+e^- \rightarrow e^+e^-(\omega J/\psi)$	Belle [53] (7.7), BABAR [23] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{2+}$	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle [54] (6.0)	2007	NC!
				$e^+e^- \rightarrow J/\psi(\dots)$	Belle [20] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \rightarrow \gamma(D\bar{D})$	BABAR [55] (np), Belle [56] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \rightarrow \gamma(\pi^+\pi^-J/\psi)$	Belle [57] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?$	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), BABAR [59] (1.1)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{2+}$	$B \rightarrow K(\phi J/\psi)$	CDF [60, 61] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{2+}$	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle [54] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?$	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), BABAR [59] (2.0)	2008	NC!
				$e^+e^- \rightarrow \gamma(\pi^+\pi^-J/\psi)$	BABAR [62, 63] (8.0)		
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}		CLEO [64] (5.4), Belle [57] (15)	2005	OK
				$e^+e^- \rightarrow (\pi^+\pi^-J/\psi)$	CLEO [65] (11)		
				$e^+e^- \rightarrow (\pi^0\pi^0J/\psi)$	CLEO [65] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{2+}$	$B \rightarrow K(\phi J/\psi)$	CDF [61] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{2+}$	$e^+e^- \rightarrow e^+e^-(\phi J/\psi)$	Belle [66] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \rightarrow \gamma(\pi^+\pi^-\psi(2S))$	BABAR [67] (np), Belle [68] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	$?$	$B \rightarrow K(\pi^+\psi(2S))$	Belle [69, 70] (6.4), BABAR [71] (2.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \rightarrow \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [72] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \rightarrow \gamma(\pi^+\pi^-\psi(2S))$	Belle [68] (5.8)	2007	NC!

Current Status

Proliferation of 'charmonium-like' resonances presents challenges

- *Too many states for charmonium spectrum, & disagreement with predicted masses, widths, decay rates*

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Even the X(3872) is not understood, ten years after discovery, with quantum numbers confirmed, and with many thousand events seen by multiple experiments

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⇒ **We need more data!**

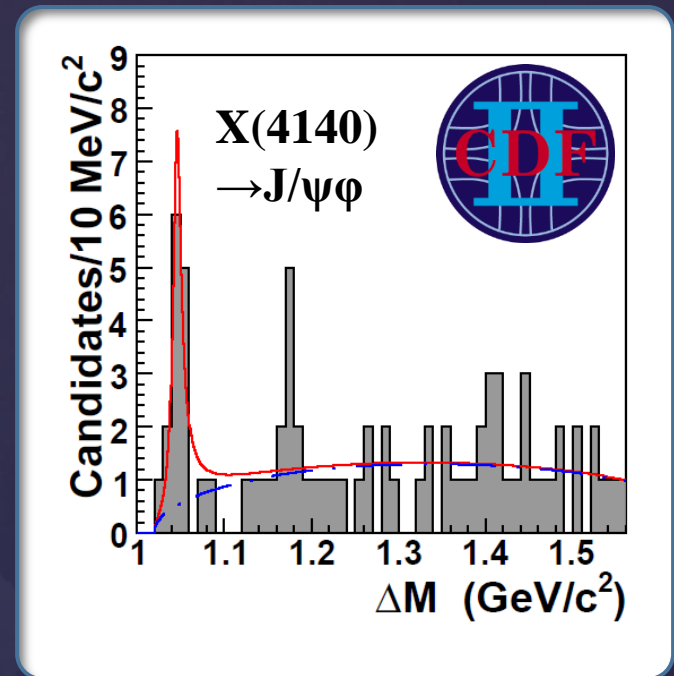
Observe zoo of mesons/baryons → Gell-Mann/Zweig develop CQM

Observe, confirm, and study as many exotic states as possible → develop more complete model of bound quark states.

X(4140)

March 2009: CDF report evidence for narrow peak in $J/\psi\phi$ spectrum, close to threshold, in decays $B^+ \rightarrow J/\psi\phi K^+$

PRL 102 242002 (2009)



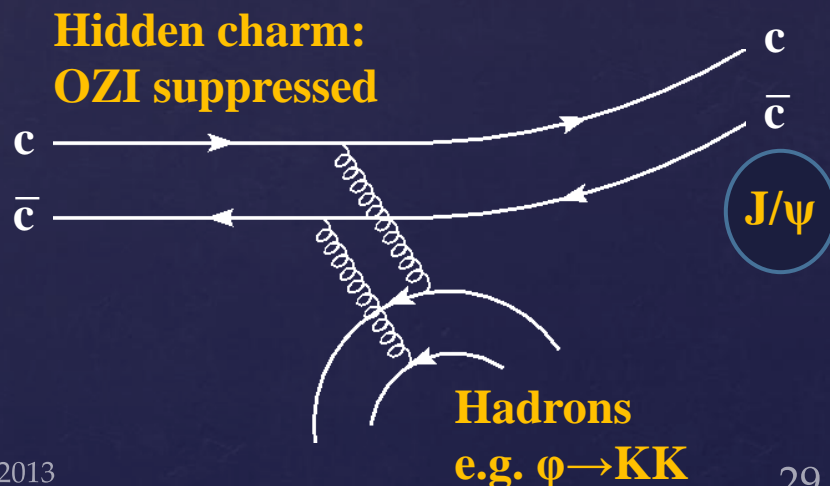
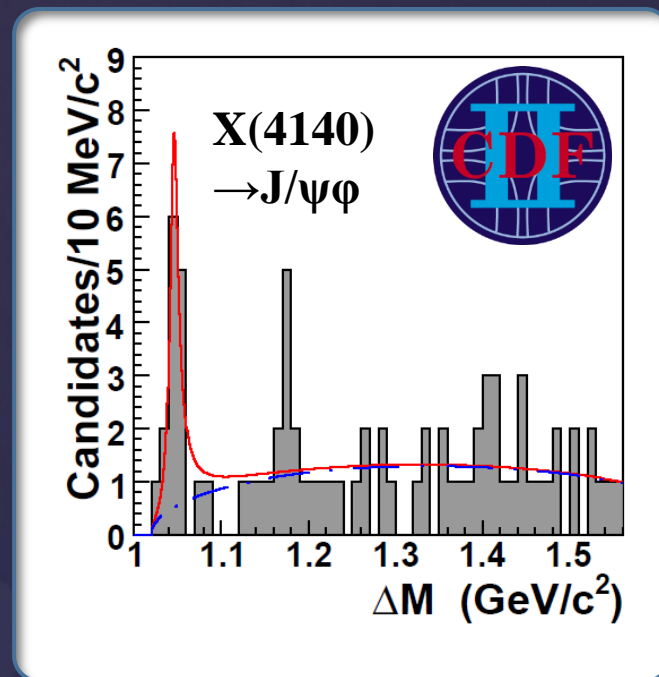
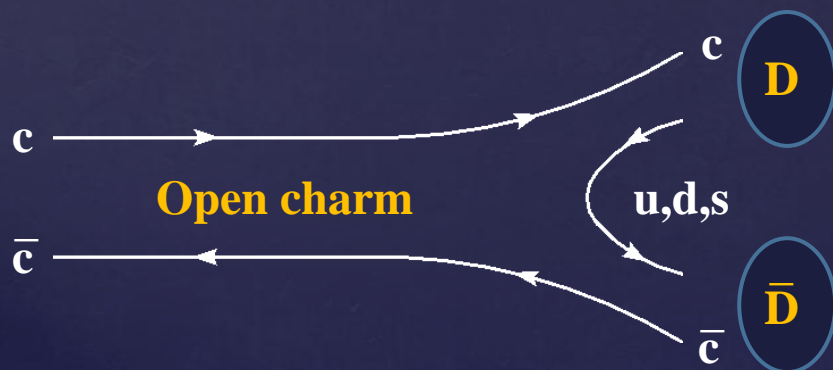
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PRL 102 242002 (2009)

Interpretation:

Mass well above 3730 MeV open charm threshold – conventional charmonium should decay into (DD), with tiny BR to $J/\psi\phi$



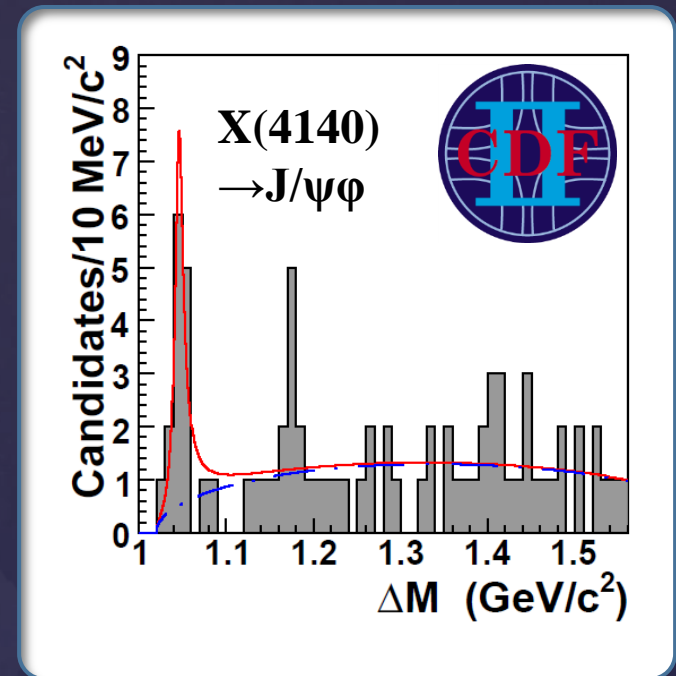
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PRL 102 242002 (2009)

Interpretation:

$X(4140) \rightarrow J/\psi\phi \Rightarrow C\text{-parity} = +1$



\Rightarrow Possible states:

0^{++}	1^{++}	2^{++}	0^{-+}	1^{-+}	2^{-+}	3^{-+}
$\underbrace{\hspace{10em}}$			$\underbrace{\hspace{10em}}$			
S-wave coupling			P-wave coupling			

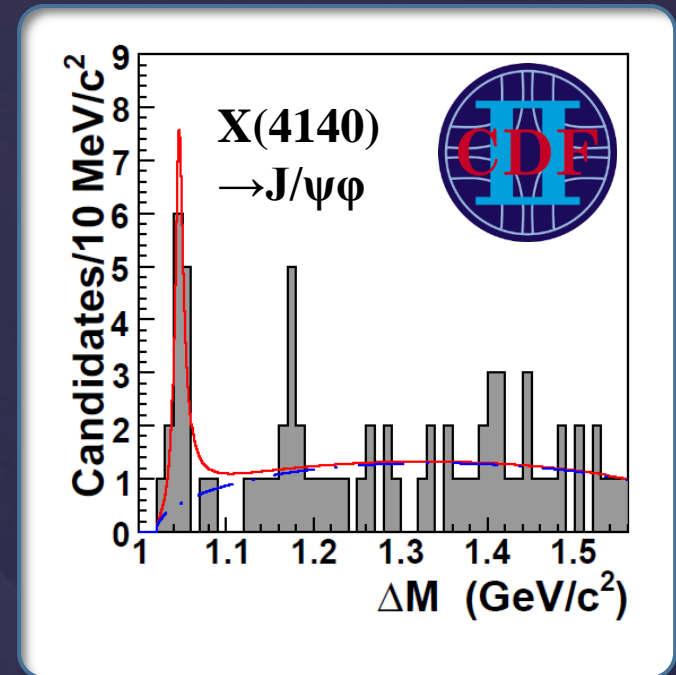
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August 2009: Belle search for this state in same channel – see no X(4140) signal

Set limit on production rate, but cannot exclude CDF peak

Lepton-photon 2009 (e.g. arXiv:0910.3138)



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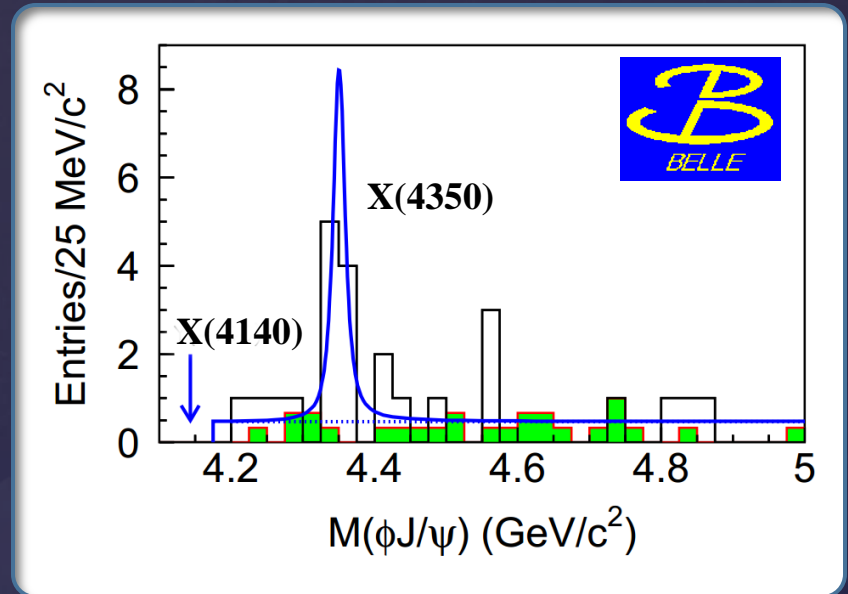
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December 2009: Belle search for direct production $\gamma\gamma \rightarrow J/\psi\phi$, allowed if X(4140) is 0^{++} or 2^{++}

No X(4140) signal – disfavors $D_s^* D_s^*$ meson molecule interpretation

But... see 3.2σ excess at 4350 MeV

PRL 104 112004 (2010)



X(4140)

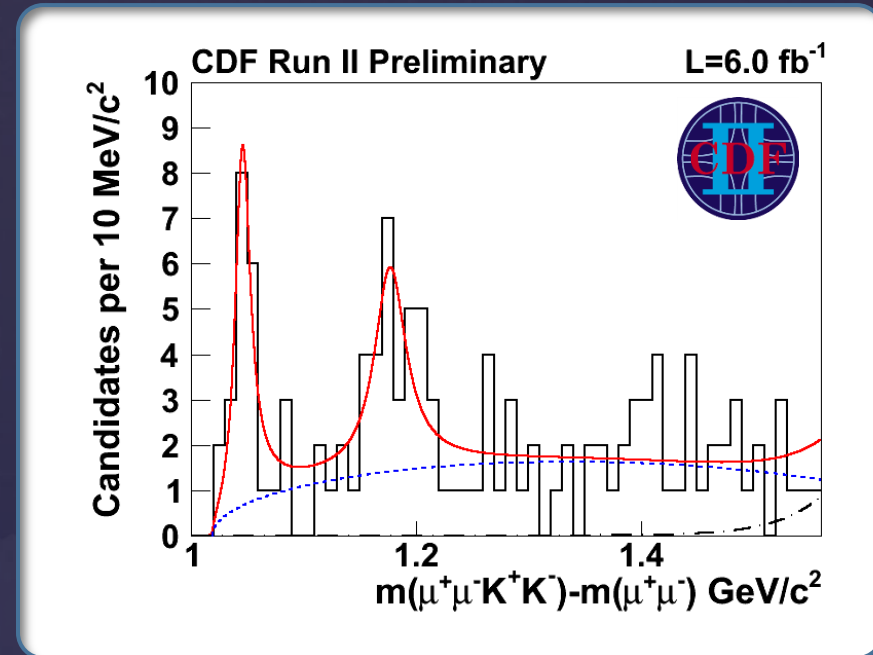
March 2009: CDF report evidence for narrow peak in $J/\psi\phi$ spectrum, close to threshold, in decays $B^+ \rightarrow J/\psi\phi K^+$

August 2009: Belle search for this state in same channel – see no X(4140) signal

December 2009: Belle search for direct production $\gamma\gamma \rightarrow J/\psi\phi$, allowed if X(4140) is 0^{++} or 2^{++}

January 2011: CDF update analysis with larger dataset: **observe X(4140) with 5σ significance**

arXiv:1101.6058



CDF also see 3σ evidence for higher mass peak, but inconsistent with Belle mass

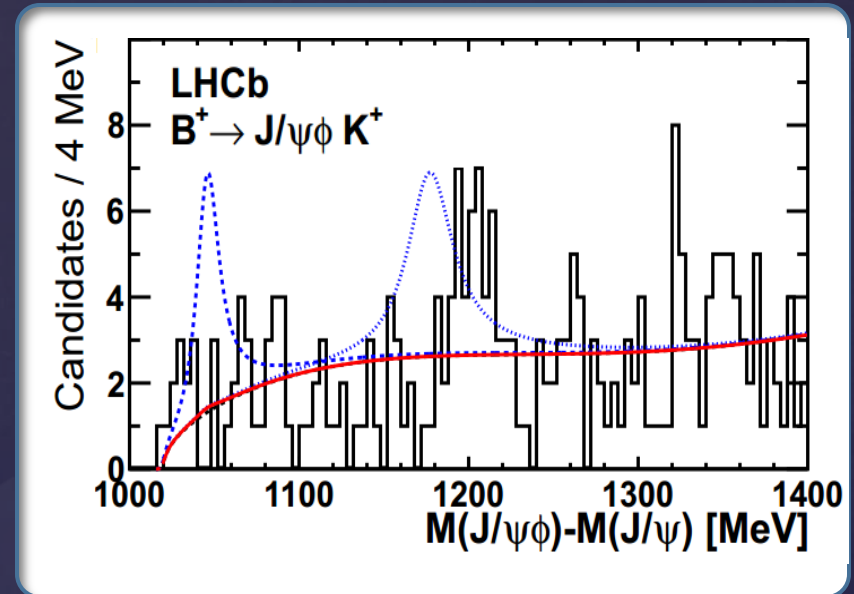
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February 2012: LHCb search in $B^+ \rightarrow J/\psi\phi K^+$ channel, see no X(4140) peak, **set limit at 2.4σ tension with CDF.**

PRD 85 091103(R) (2012)

X(4140)

Is X(4140) real?

If so, what is it?

Multiple interpretations (conventional $c\bar{c}$, DD molecule, $c\bar{c}q\bar{q}$ tetraquark, hybrid state, threshold effect...), none convincing yet.

Need additional data to resolve the X(4140) puzzle

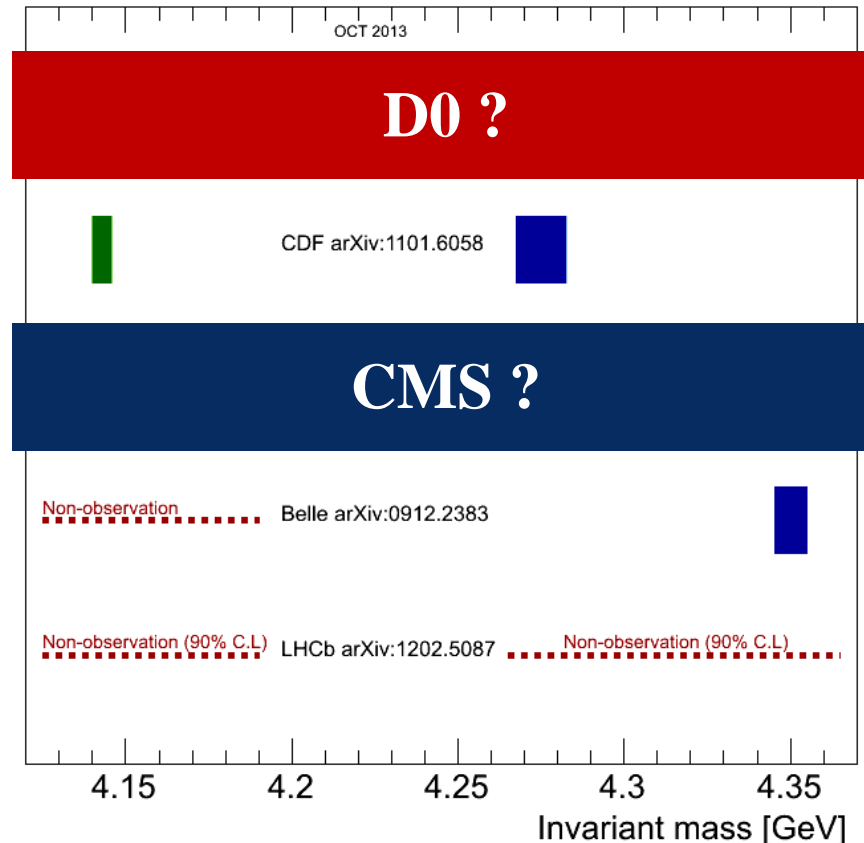
Today: Search results from D0 and CMS



Experimental status in the search for X(4140) and additional structures

Significance: ■ $<3\sigma$ ■ $3-4\sigma$ ■ $>5\sigma$

stat.
tot.



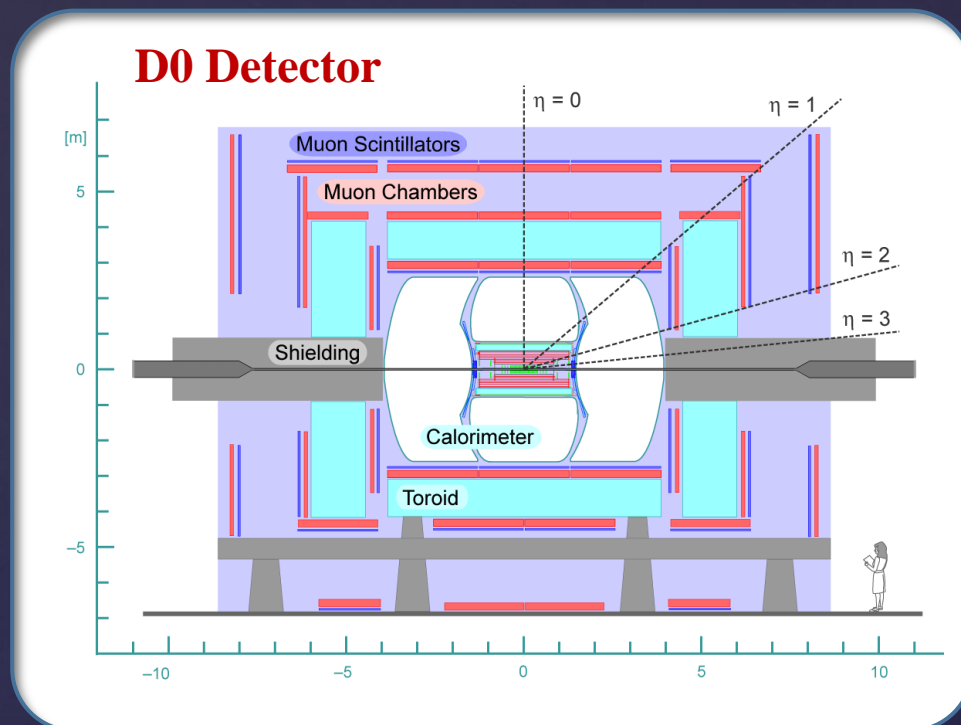
The D0 Detector



Strengths for this analysis:

- Wide muon system coverage
- Thick shielding before muon system, suppresses backgrounds
- Efficient muon triggers
- Good Impact Parameter resolution

But... no π/K separation: need care to avoid pion backgrounds in $\mu\mu KKK$ final state



Use full 10.4 fb^{-1} dataset of $p\bar{p}$ collisions

Collect sample with single and dimuon triggers

Search Strategy



1) Establish $B^+ \rightarrow J/\psi \phi K^+$ signal

- **Cut-based analysis** : avoids possible kinematic shaping
- Use B^+ sideband data to model background behavior
- Use $B^+ \rightarrow J/\psi \phi K^+$ Monte Carlo simulation (3-body phase space decay) to model signal
- Search for and **veto any known or unknown resonances** in J/ψ X system ($X = 1, 2, 3$ tracks)

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2) After finalizing selection, search for intermediate $X \rightarrow J/\psi \phi$ decay

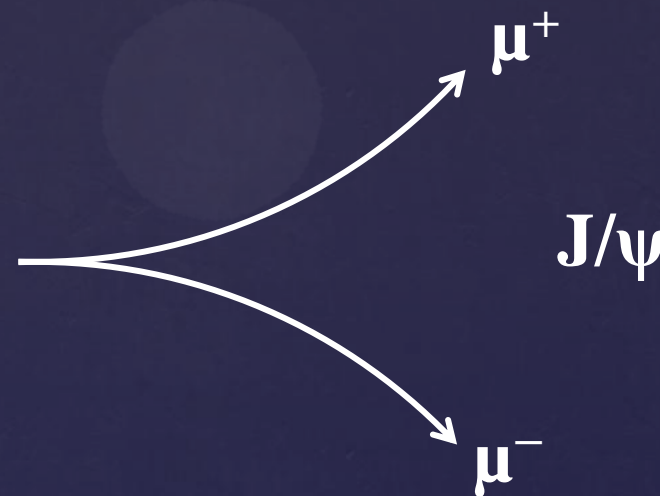
- Define **search window** for $X(4140)$ state: < 4200 MeV
- Fit $M(J/\psi \phi)$ to establish significance, mass, width, and yield of any possible signal

Event Selection



1) Require two muons of opposite charge

- Mass consistent with $J/\psi \rightarrow \mu\mu$:
 $2.9 < M(\mu\mu) < 3.3 \text{ GeV}$
- Trajectories consistent with a common vertex
- ≥ 1 muon must have hits on both sides of toroid



Event Selection



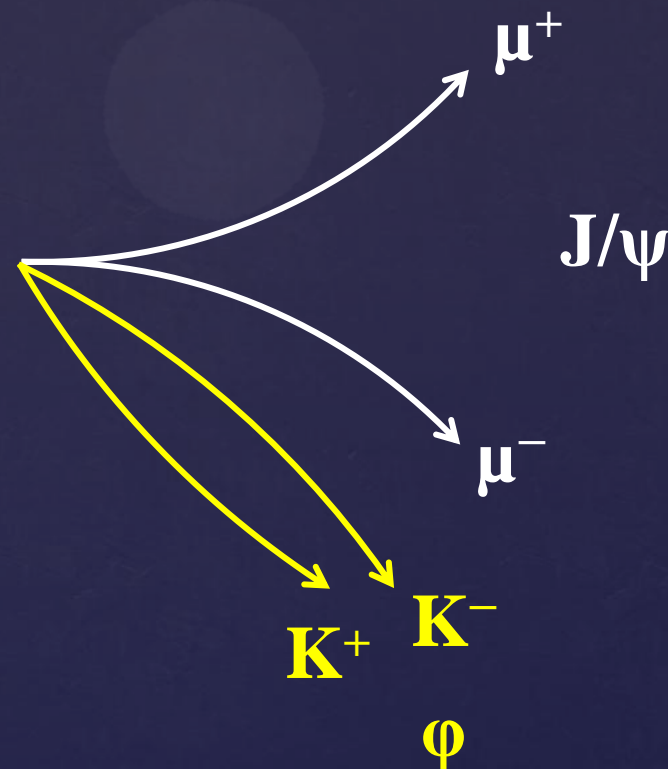
1) Require two muons of opposite charge

2) Require two tracks of opposite charge

- Assigned the charged kaon mass
- Mass consistent with $\phi \rightarrow KK$:

$$1.005 < M(KK) < 1.035 \text{ GeV}$$

(Narrow state – helps BG rejection)



Event Selection

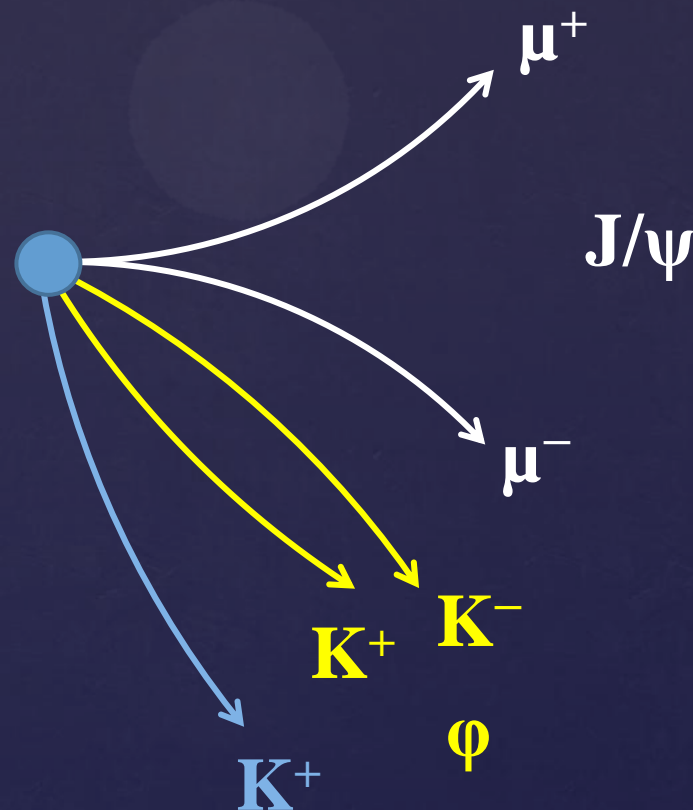


1) Require two muons of opposite charge

2) Require two tracks of opposite charge

3) Combine with additional track

- Assigned the charged kaon mass
- 5-track system constrained to a common vertex:
 $\chi^2 < 20/6$ d.o.f.
- 3rd kaon must have ≥ 3 silicon hits



Event Selection



1) Require two muons of opposite charge

2) Require two tracks of opposite charge

3) Combine with additional track

4) Reconstruct B^+ candidate

- Mass consistent with B meson:

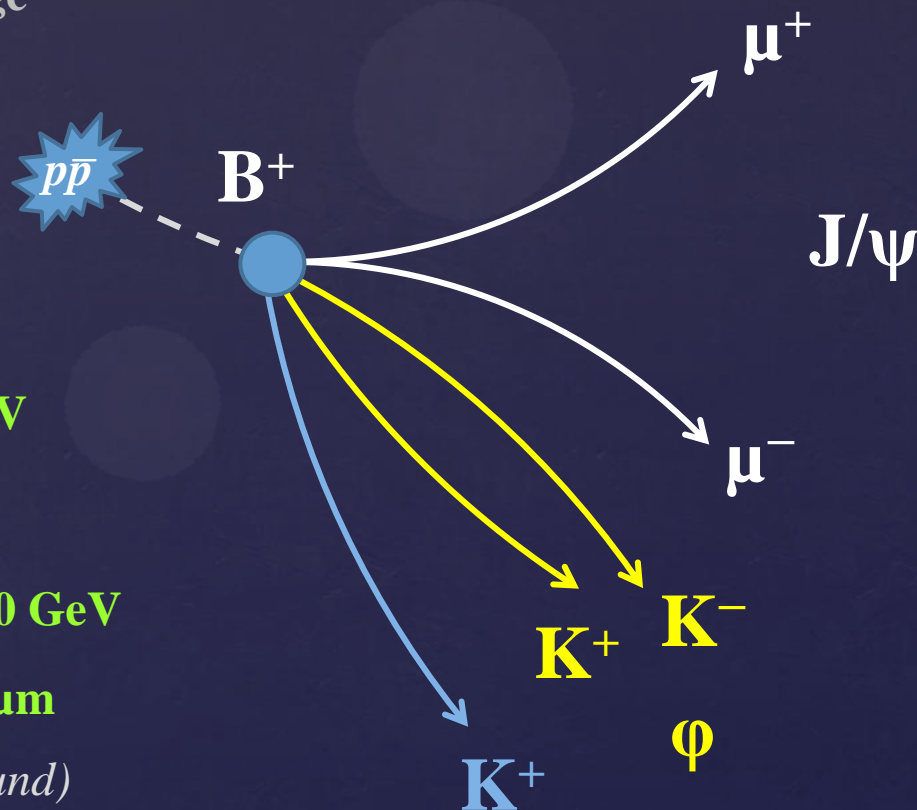
$$5.23 < M(J/\psi KKK) < 5.33 \text{ GeV}$$

(with $M(\mu\mu) \equiv M^{PDG}(J/\psi)$)

- Transverse momentum $7 < p_T(B^+) < 30 \text{ GeV}$

- Transverse decay length $L_{xy}(B) > 250\mu\text{m}$

(suppresses prompt J/ψ background)

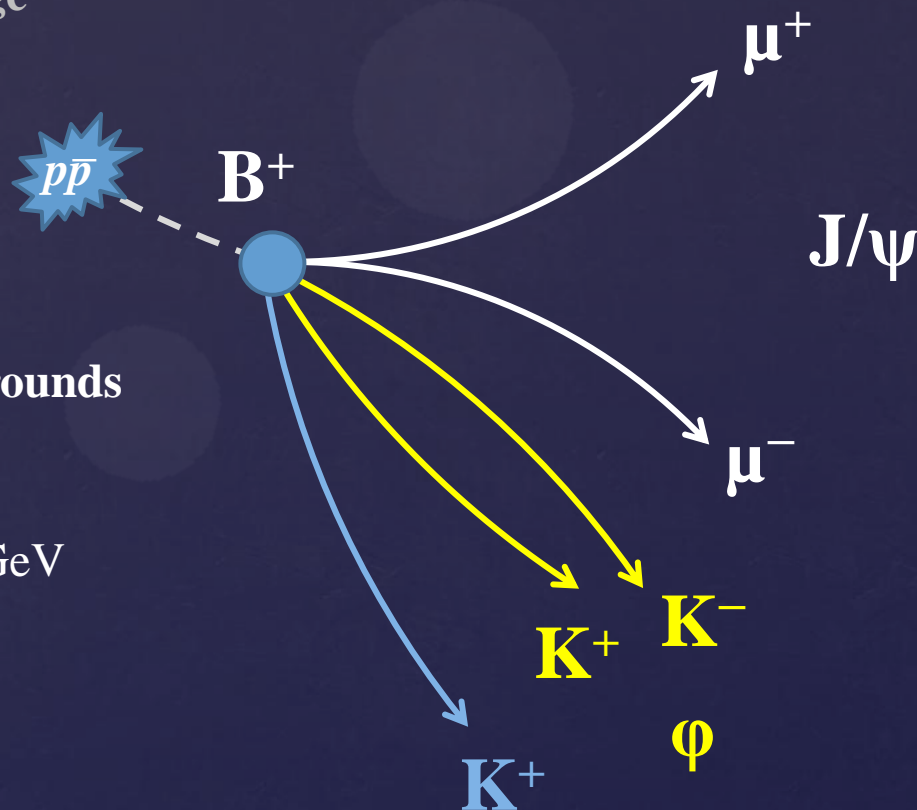


Event Selection



- 1) Require two muons of opposite charge
- 2) Require two tracks of opposite charge
- 3) Combine with additional track
- 4) Reconstruct B^+ candidate
- 5) Apply cuts to remove physics backgrounds
 - Veto $B \rightarrow \psi(2S) + X$ events
 - Remove events with $M(J/\psi\phi) > 4.59 \text{ GeV}$

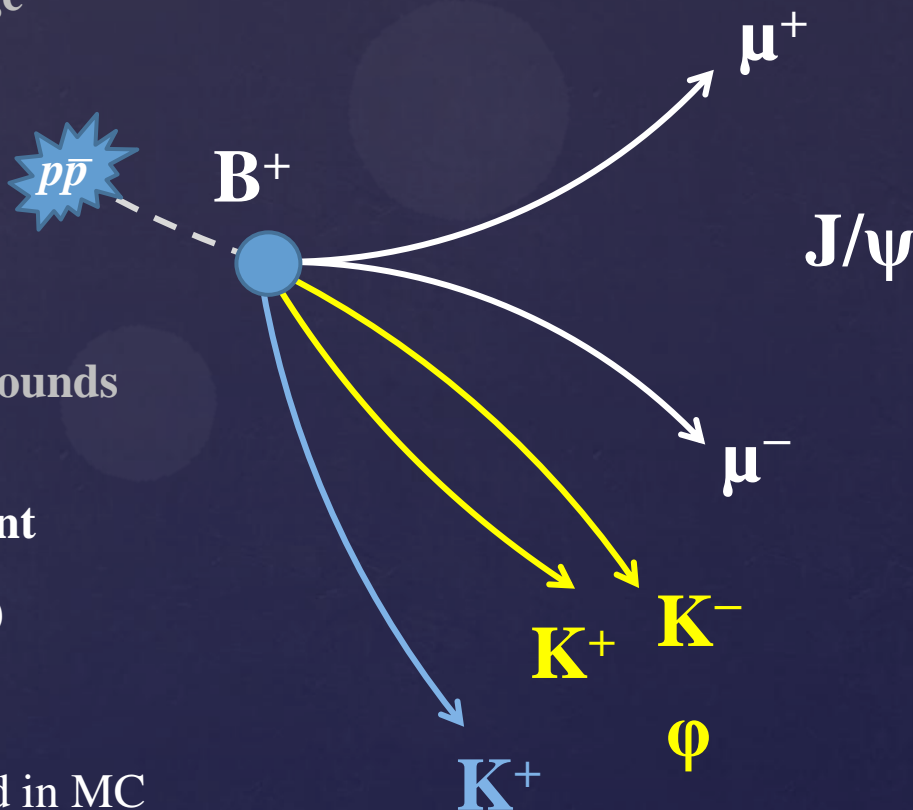
More later...



Event Selection



- 1) Require two muons of opposite charge
- 2) Require two tracks of opposite charge
- 3) Combine with additional track
- 4) Reconstruct B^+ candidate
- 5) Apply cuts to remove physics backgrounds
- 6) Choose best **single candidate** per event
 - Pick candidate with lowest $M(\phi \rightarrow KK)$
 - 95% efficient for signal
 - Possible sampling bias tested/corrected in MC



Chasing $B^+ \rightarrow J/\psi \phi K^+$ Signal



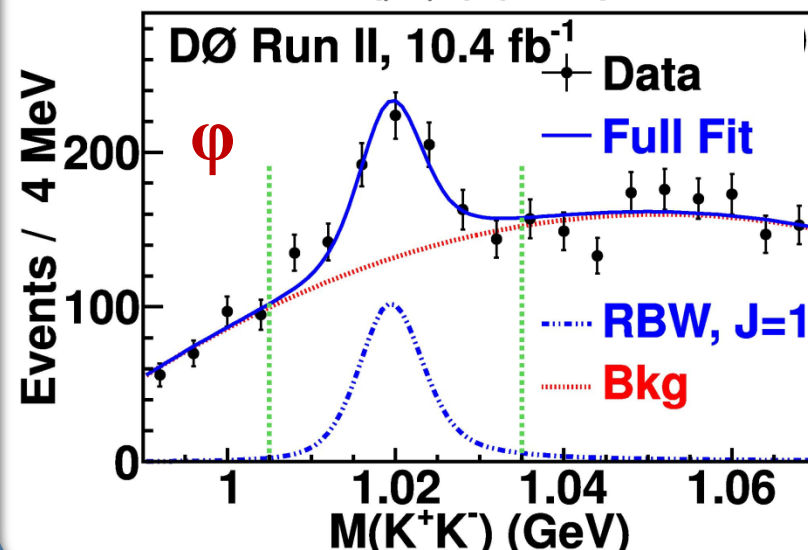
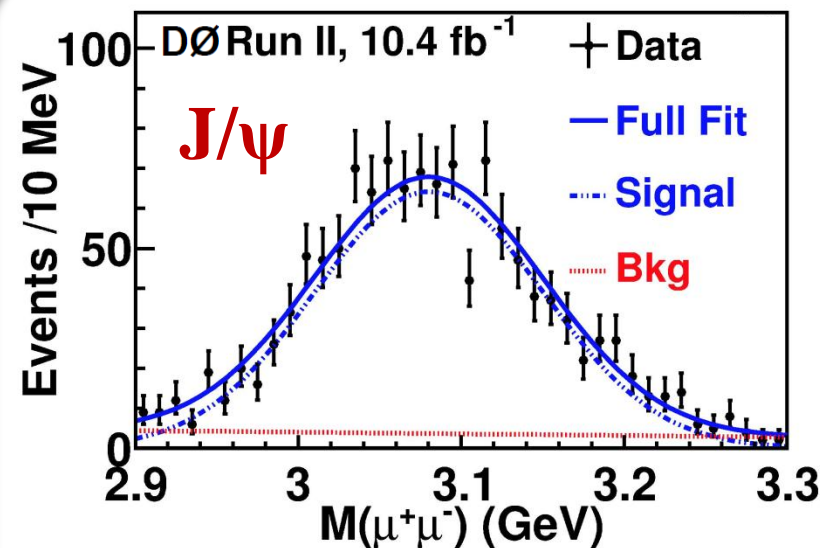
Total of **1269** events pass all selections

Very high J/ψ purity in signal sample
(~90%)

- $N(J/\psi) = 1124 \pm 70$ events
- Excellent muon triggers and ID

Clear narrow $\phi \rightarrow K^+ K^-$ peak above combinatorial background

- $N(\phi) = 284 \pm 40$ events



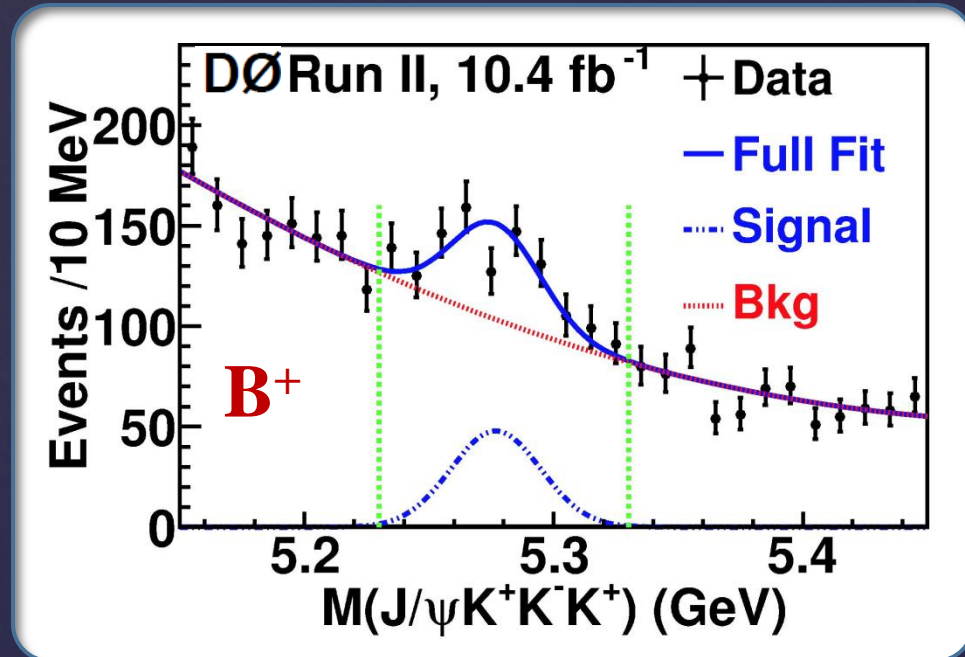
Chasing $B^+ \rightarrow J/\psi \phi K^+$ Signal



$B^+ \rightarrow J/\psi \phi K$ peak observed above a smooth combinatorial background

Binned maximum likelihood fit used to extract signal

- Gaussian signal model
 - Width fixed to 18 MeV from simulation
 - Consistent results obtained with free width
- Quadratic background model



$$N(B^+) = 215 \pm 37 \text{ events}$$

$$M(B^+) = 5277.8 \pm 3.3 \text{ MeV}$$

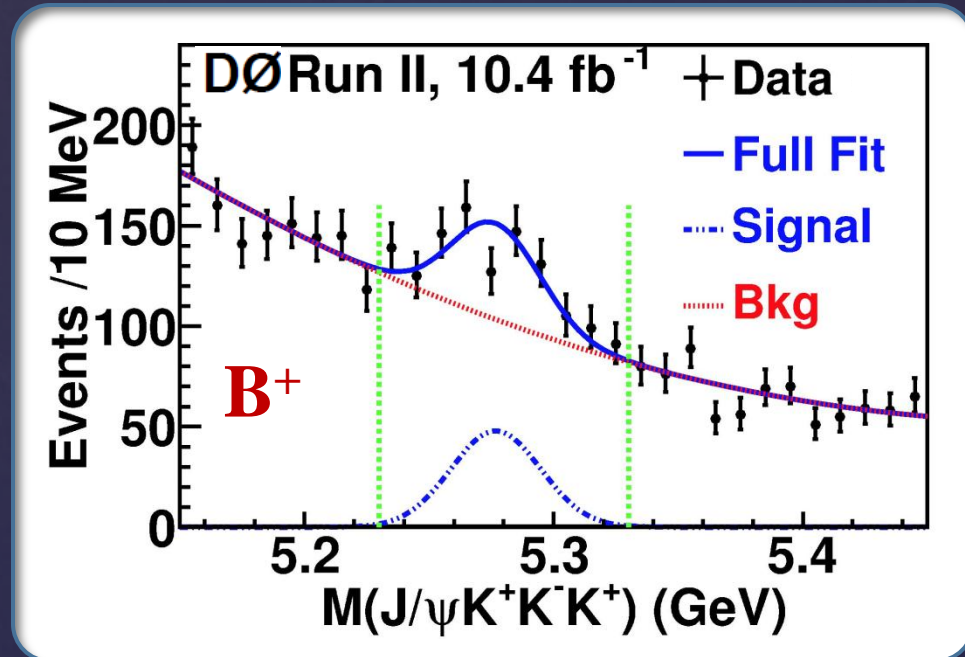
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B^+ signal established → Can now search for intermediate $J/\psi \phi$ resonances

Peaking Backgrounds



No particle ID to distinguish K/π

\Rightarrow Need to check for any peaking background from J/ψ X resonances
(X = 1, 2, or 3 tracks)

- Resonance in any sub-system may create an enhancement in the $M(J/\psi\phi)$ or $M(J/\psi\phi K)$ distributions
- Identifying and removing resonances will reduce backgrounds
- Finding a resonance and fitting its mass validates the mass scale and momentum resolution

Peaking Backgrounds: $J/\psi \pi^+ \pi^-$



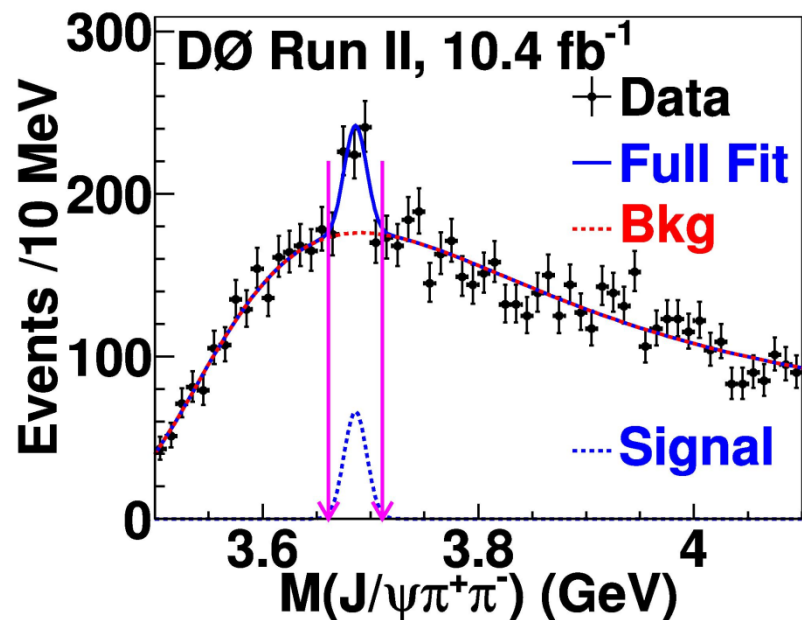
Expect contribution
from:

$$\begin{array}{l} b \rightarrow \psi(2S) X \\ \quad \quad \quad \searrow \\ \quad \quad \quad J/\psi \pi^+ \pi^- \end{array}$$

$$B^+ \rightarrow \psi(2S) K^+ / \pi^+ / K^0 \pi^+ / \dots$$

$$B^0 \rightarrow \psi(2S) \pi^+ \pi^- / K^+ \pi^-$$

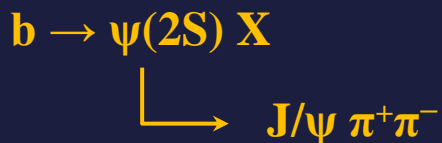
$$B_s^0 \rightarrow \psi(2S) K^+ K^-$$



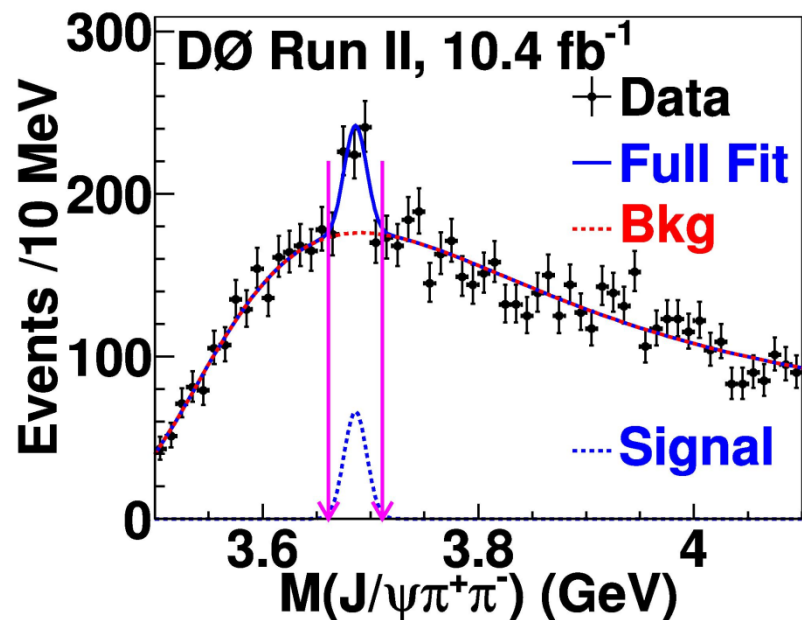
Peaking Backgrounds: $J/\psi \pi^+ \pi^-$



Expect contribution
from:



- Make all combinations of J/ψ + 2 tracks (of the 3 tracks forming the ϕK candidate)
- Assign the charged pion mass to these tracks and examine $M(J/\psi \pi^+ \pi^-)$
- $\psi(2S)$ signal observed, mass and width consistent with expectations

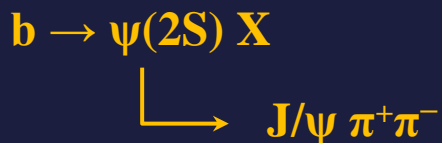


$$M[\psi(2S)] = 3685.5 \pm 2.4 \text{ MeV} \\ (\text{PDG: } 3686.1 \text{ MeV})$$

Peaking Backgrounds: $J/\psi \pi^+ \pi^-$



Expect contribution
from:



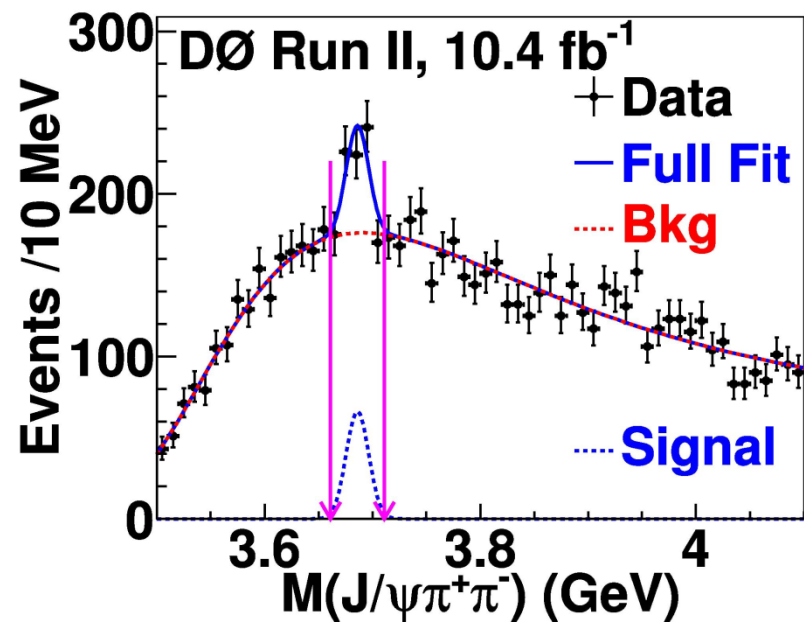
$\psi(2S)$ Veto:

Remove all events with *any of the three*
 $J/\psi + 2$ track combinations in range:

$$3661 < M(J/\psi \pi^+ \pi^-) < 3711 \text{ MeV}$$

($\pm 2.5\sigma$ from Monte Carlo simulation)

No other resonances seen in the data



$$M[\psi(2S)] = 3685.5 \pm 2.4 \text{ MeV}$$

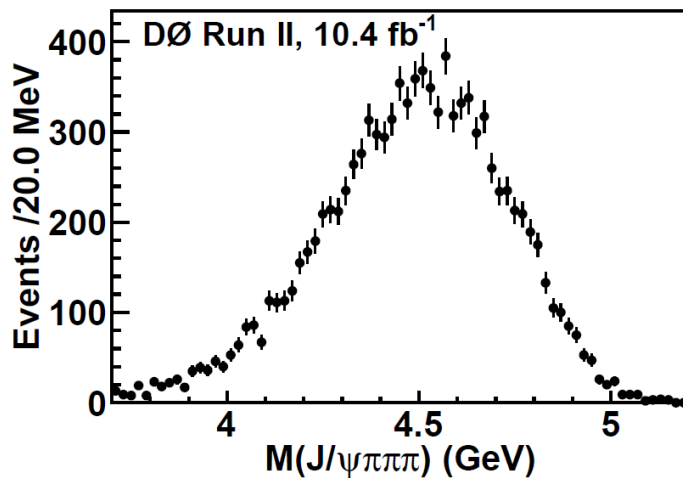
(PDG: 3686.1 MeV)

Peaking Backgrounds: $J/\psi \pi^+, K^+, \pi^+\pi^+\pi^-$

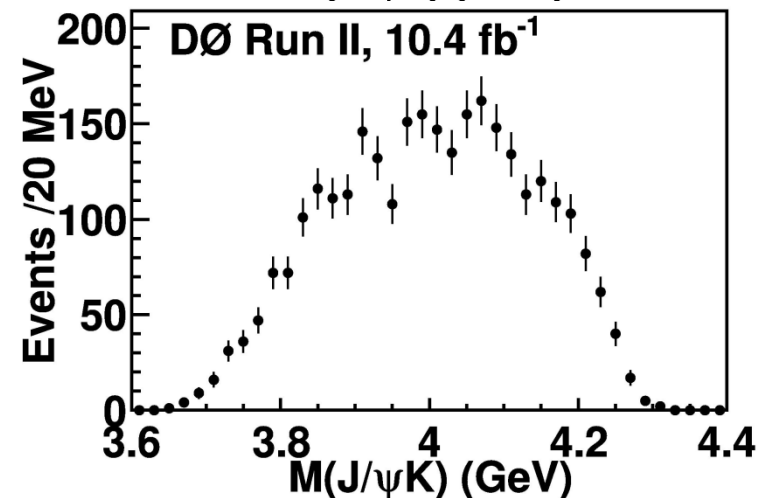
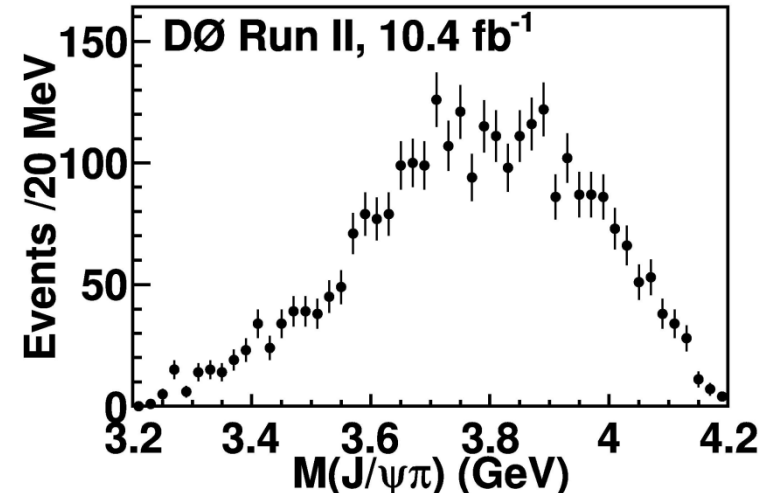
No structures observed in one- or three-track combinations

Overall shape governed by kinematic constraints, but no additional peaking behavior

$J/\psi + 3$ track combinations



$J/\psi + 1$ track combinations



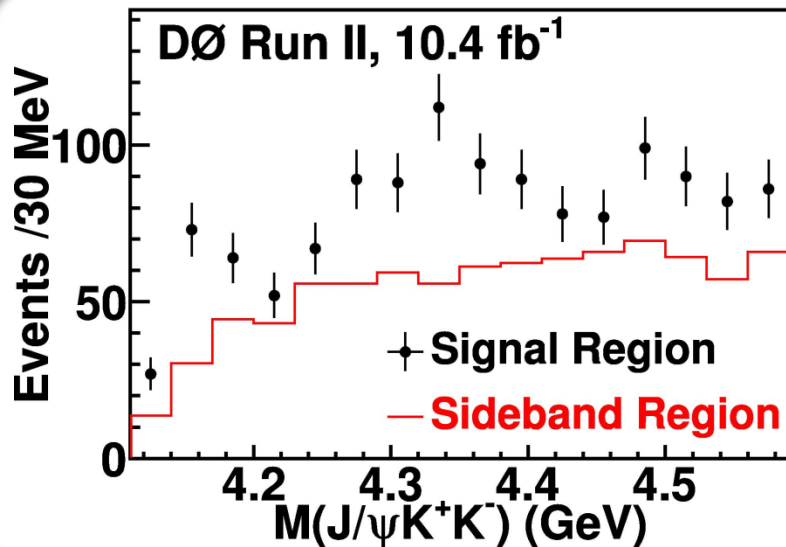
Searching for $X \rightarrow J/\psi \phi$



Strategy 1:

Plot $M(J/\psi \phi)$ for events in B^+ signal and sideband regions

- Simple approach, but limited by backgrounds
- Sidebands: $[5.15 \rightarrow 5.23 \parallel 5.33 \rightarrow 5.45]$ GeV



Searching for $X \rightarrow J/\psi \phi$

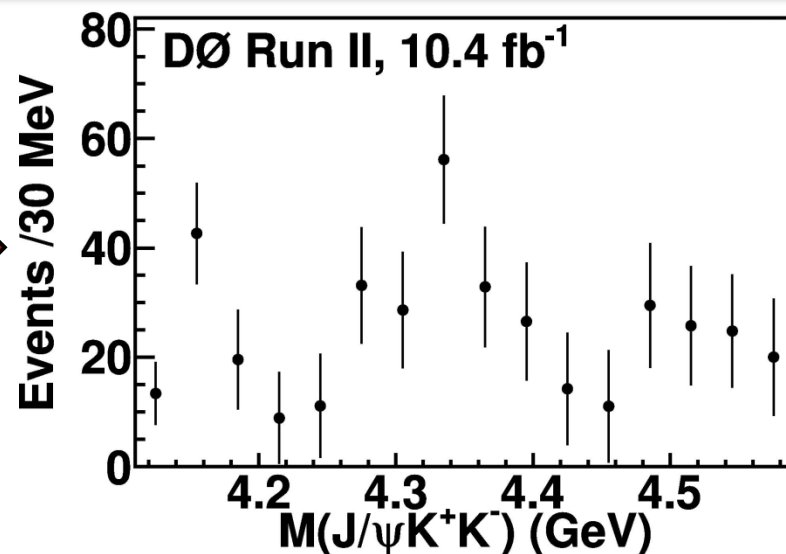
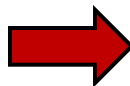
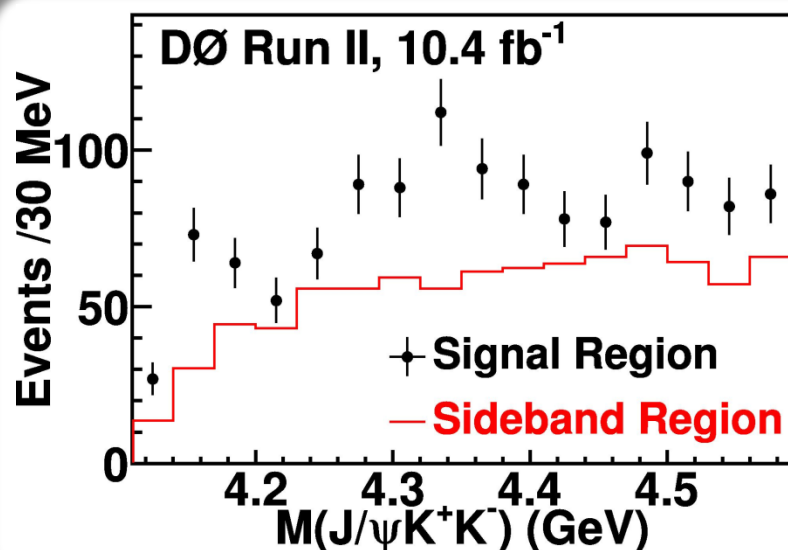


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Sideband-subtracted distribution



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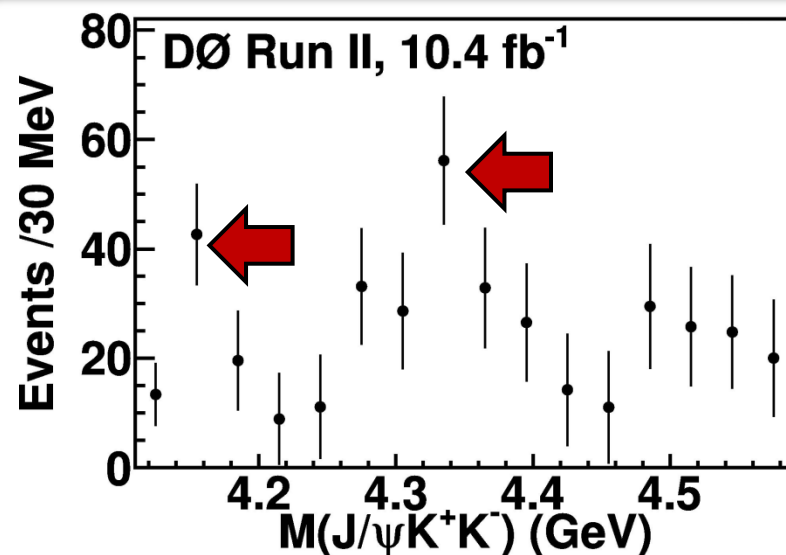
- Simple approach, but limited by backgrounds
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Distribution inconsistent with smooth model expected from 3-body phase space

Two clear regions with excess B^+ events:

- **Narrow peak near threshold (~ 4150 MeV)**
- **Broader excess around 4350 MeV**

Sideband-subtracted distribution



Searching for $X \rightarrow J/\psi \phi$



Strategy 1:

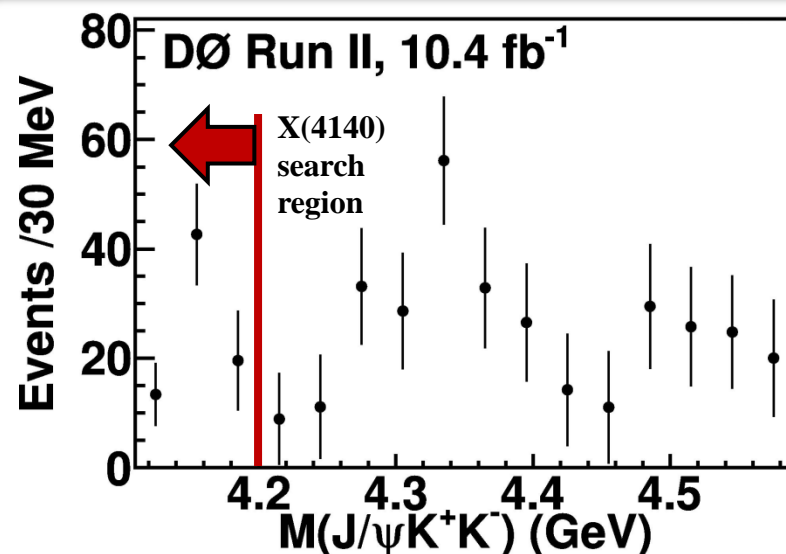
Plot $M(J/\psi \phi)$ for events in B^+ signal and sideband regions

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In search region $M(J/\psi \phi) < 4.20$ GeV:

- **80 events**
- p-value of BG fluctuation: 8×10^{-4}
(using ensemble of pseudo-experiments)

Sideband-subtracted distribution



A Better Way...



Previous method doesn't make the most of our knowledge:

- Real $B^+ \rightarrow X(4140) K^+$ events will have peak in $M(J/\psi KKK)$, of known width and position.
- By grouping samples into just two regions (signal, sidebands), we dilute the power of this information

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So... Strategy 2:

Divide sample into bins in $M(J/\psi\phi)$, and fit $M(J/\psi KKK)$ to extract B^+ yield in each bin:

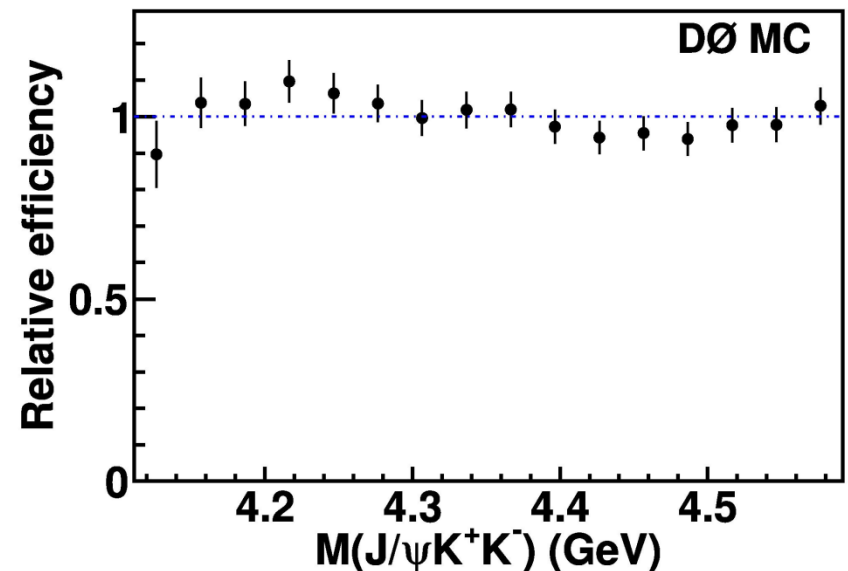
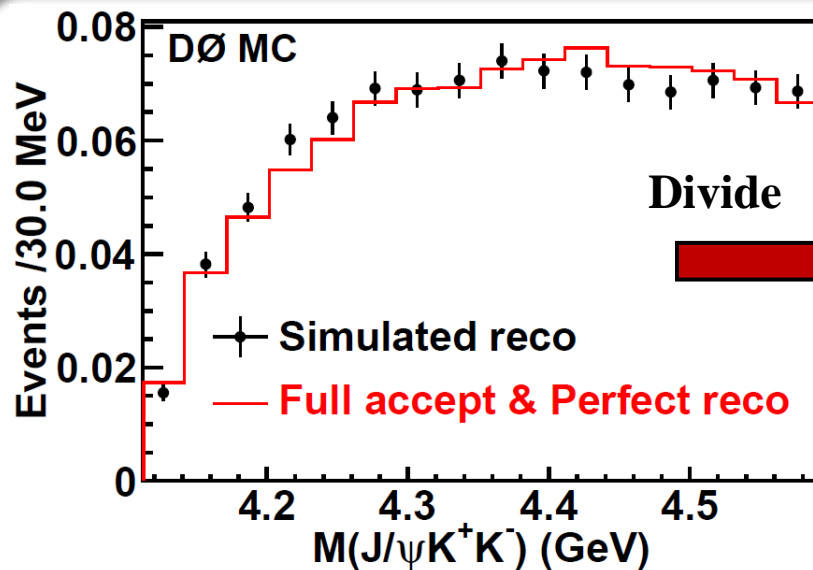
- Use MC to fix width of B^+ peak (17 – 20 MeV, bin-dependent)
- Constrain B^+ mass, and background shape, from global B^+ mass fit
- Correct for possible efficiency-dependence on $M(J/\psi\phi)$

Efficiency Correction



Use MC simulation to assess trigger, reconstruction & selection efficiency versus $M(J/\psi\phi)$

- Assume 3-body phase-space model
- Compare generated and reconstructed distributions
- Ratio gives efficiency dependence

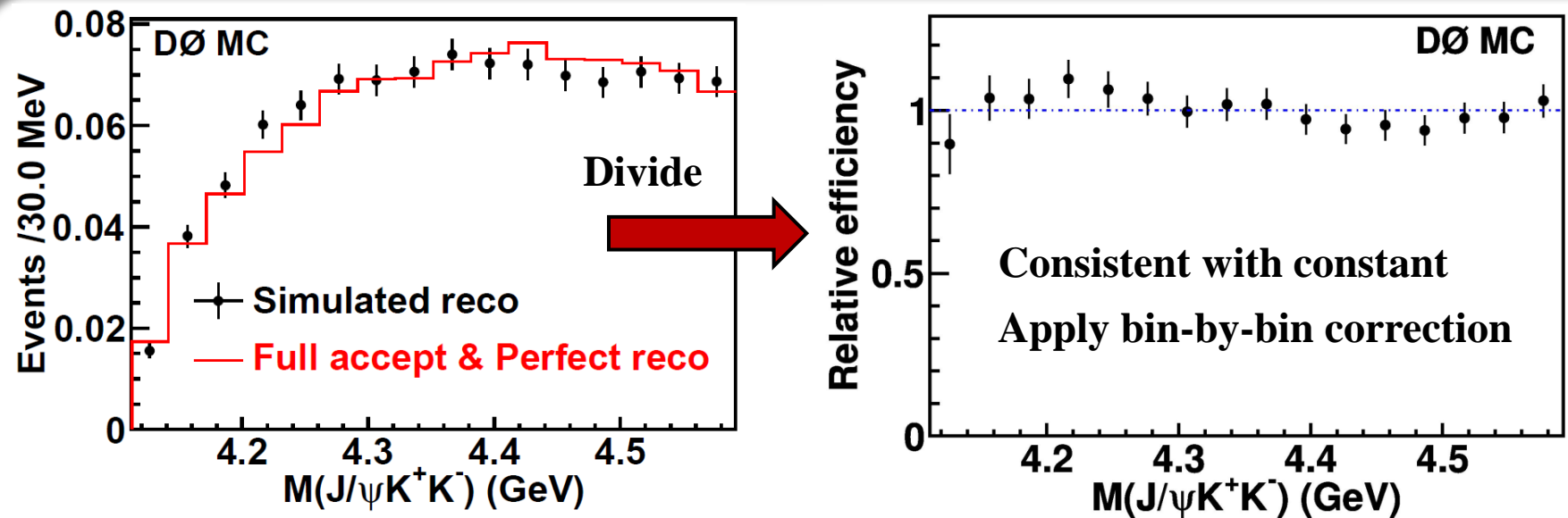


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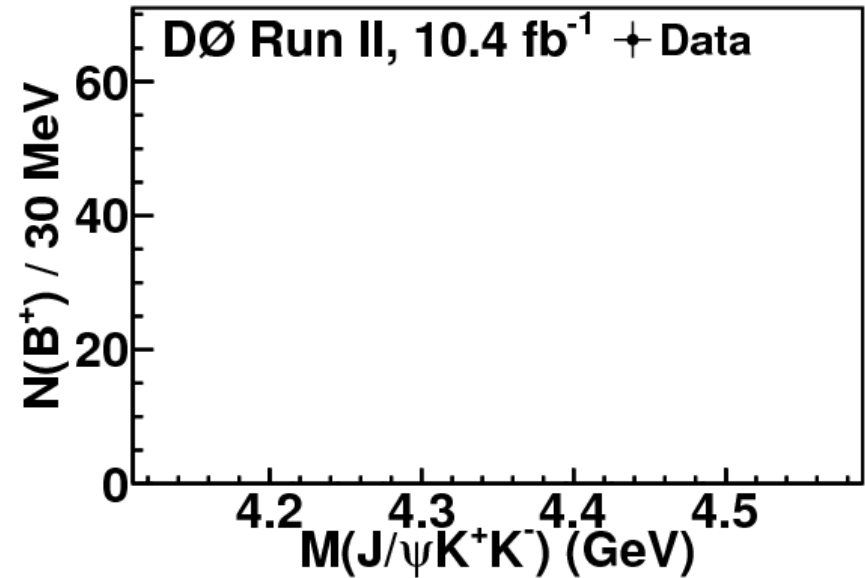


Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in $X(4140)$ search region

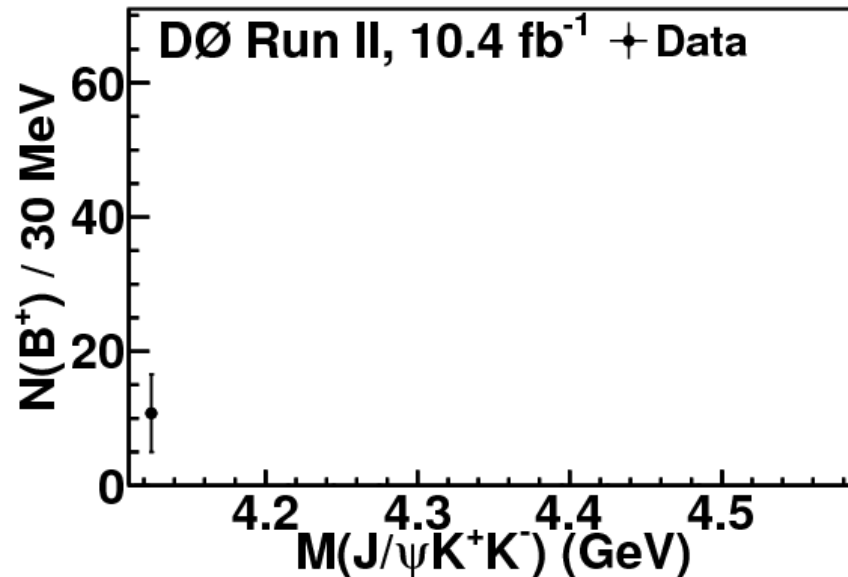
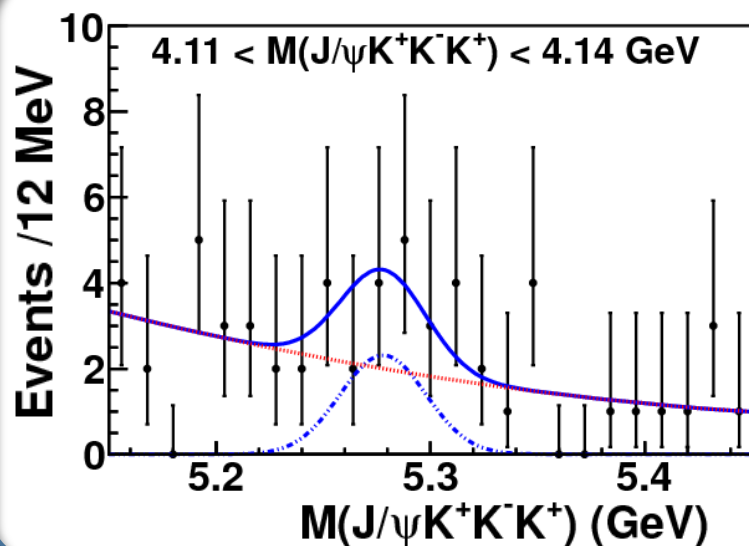


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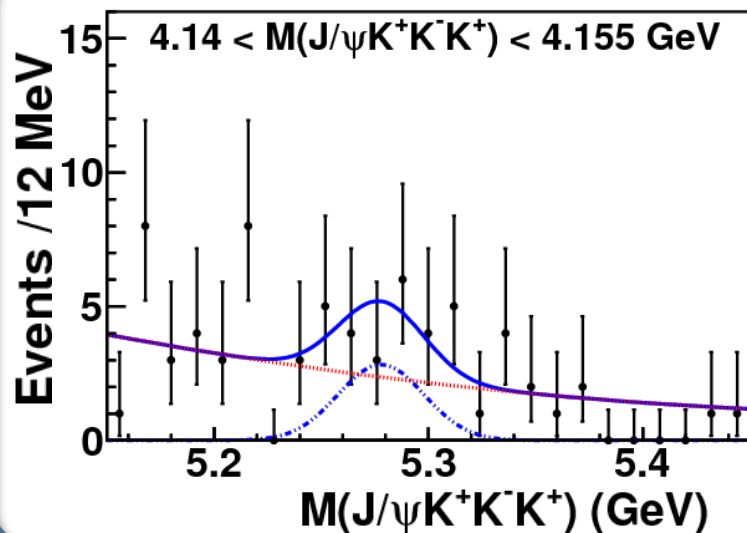


Building $M(J/\psi\phi)$ Distribution

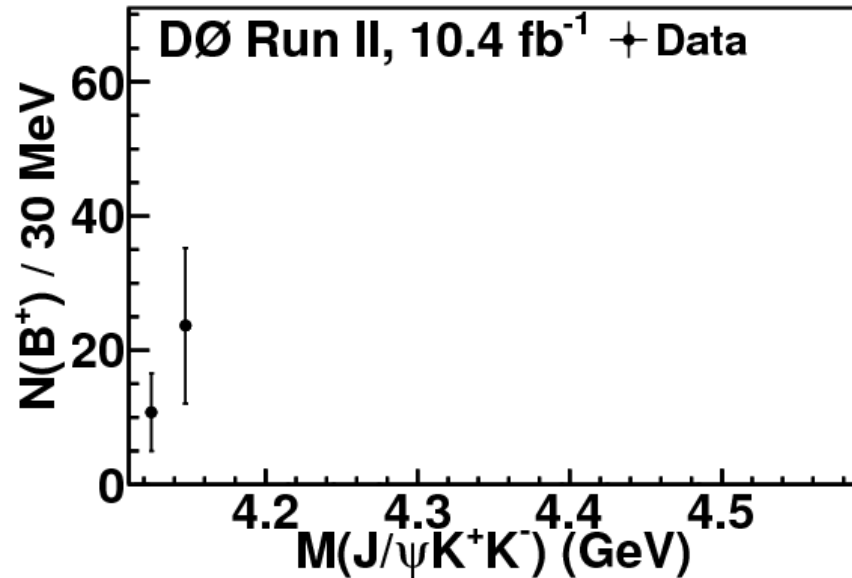


17 bins in $M(J/\psi\phi)$:

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(half-width bin)

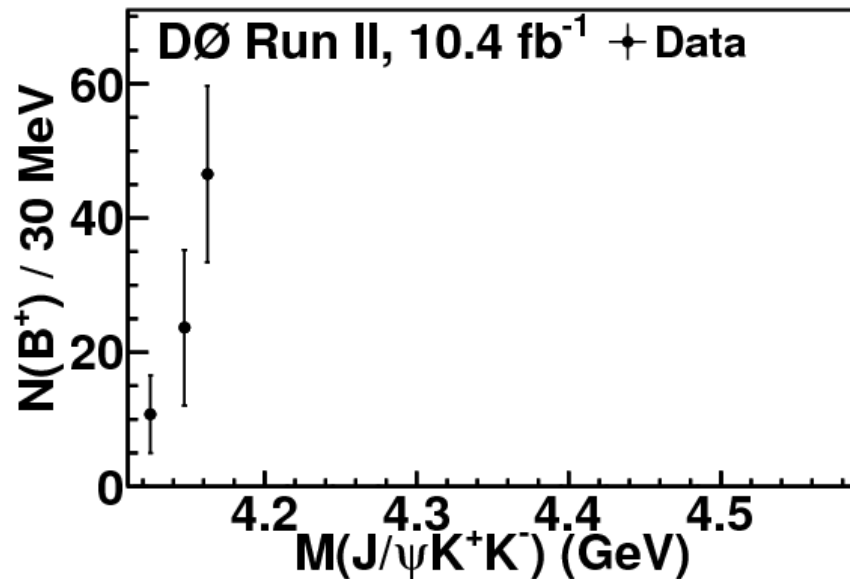
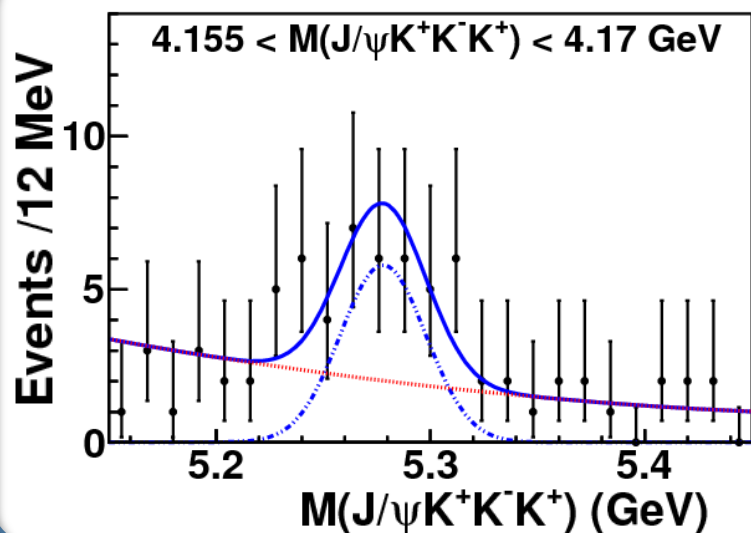


Building $M(J/\psi\phi)$ Distribution



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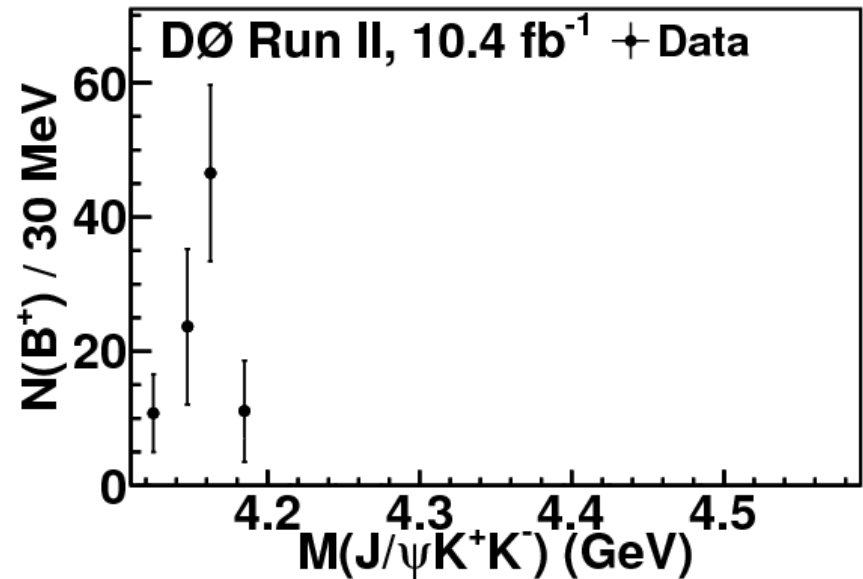
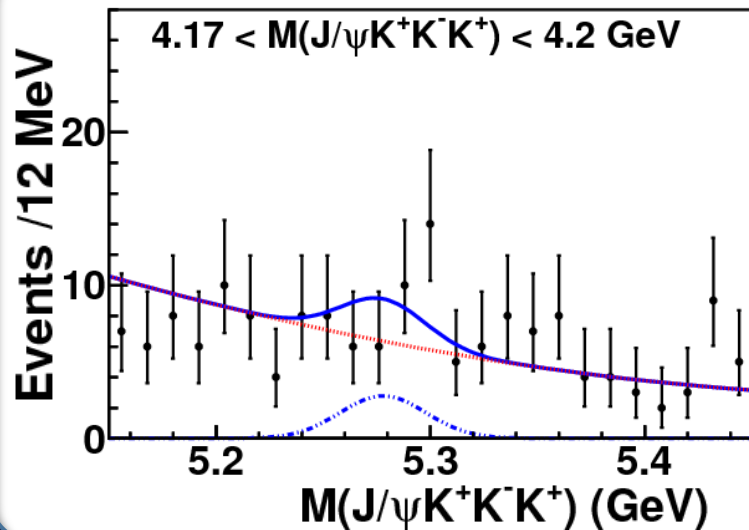
Clear B^+ peak at X(4140) region

Building $M(J/\psi\phi)$ Distribution



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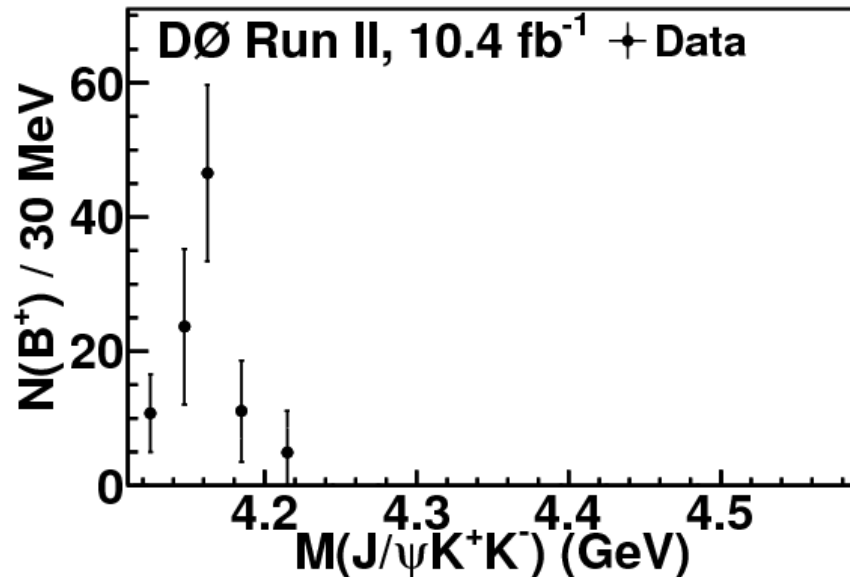
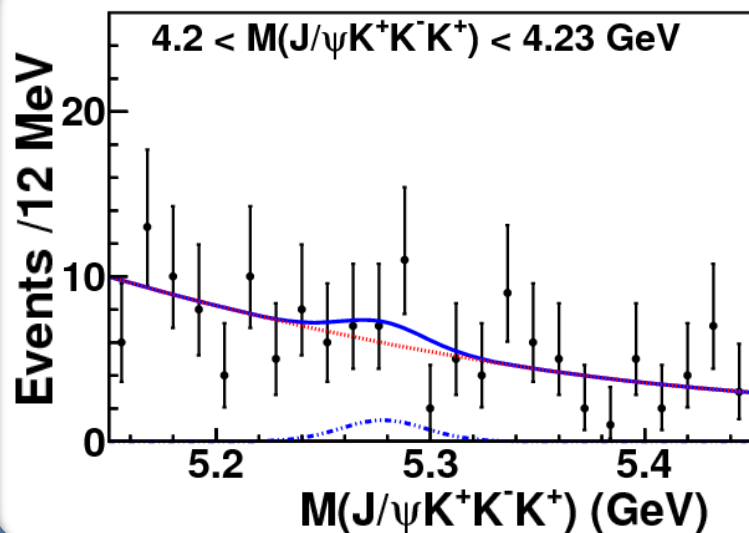
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

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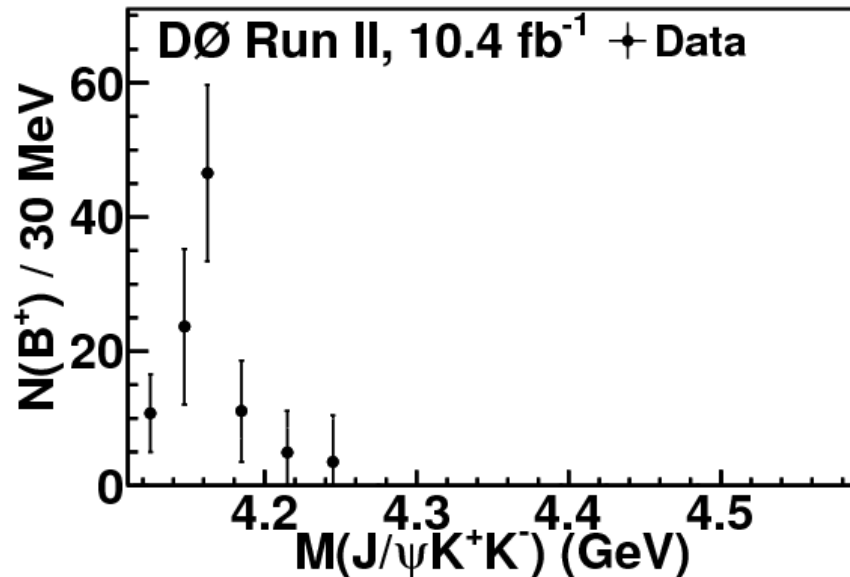
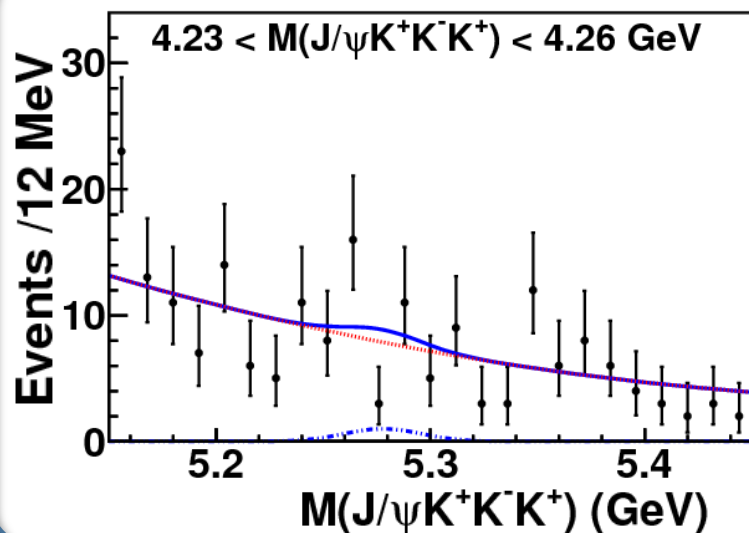
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Building $M(J/\psi\phi)$ Distribution



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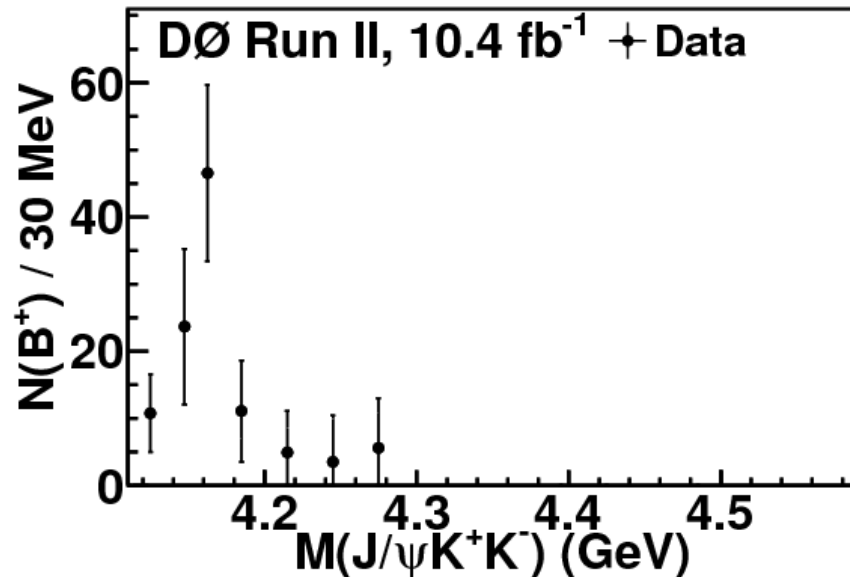
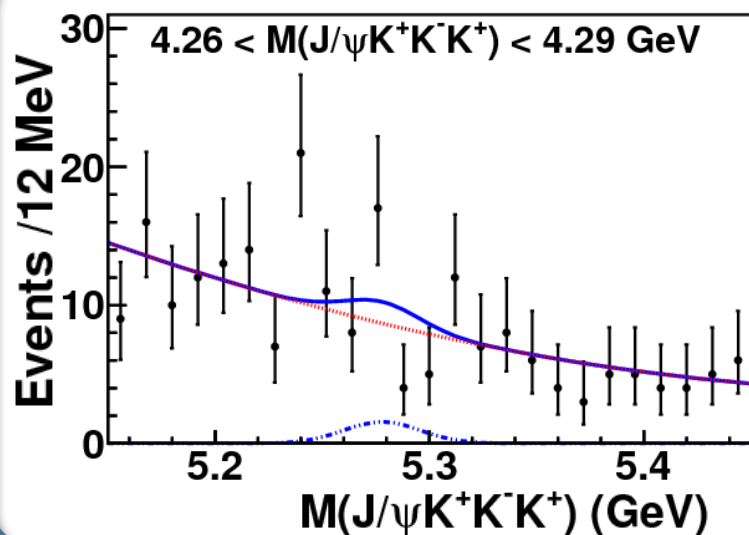
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Building $M(J/\psi\phi)$ Distribution



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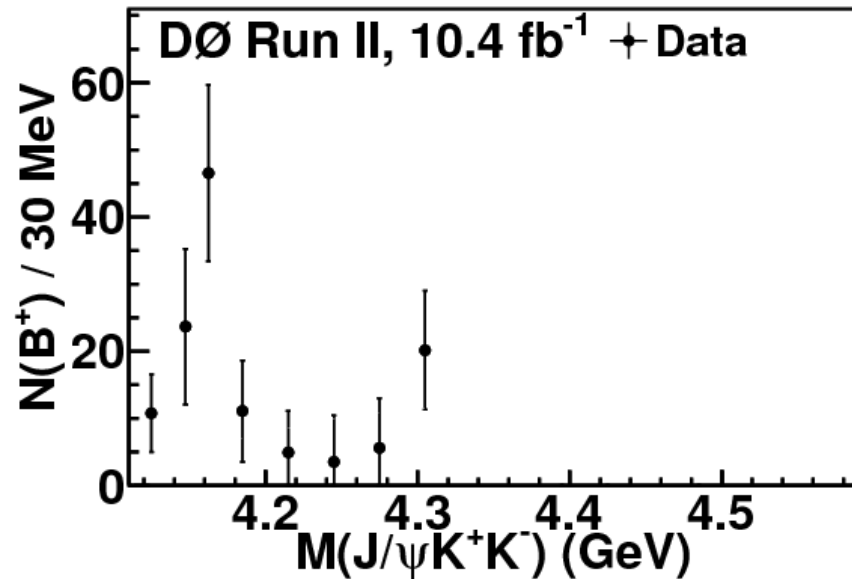
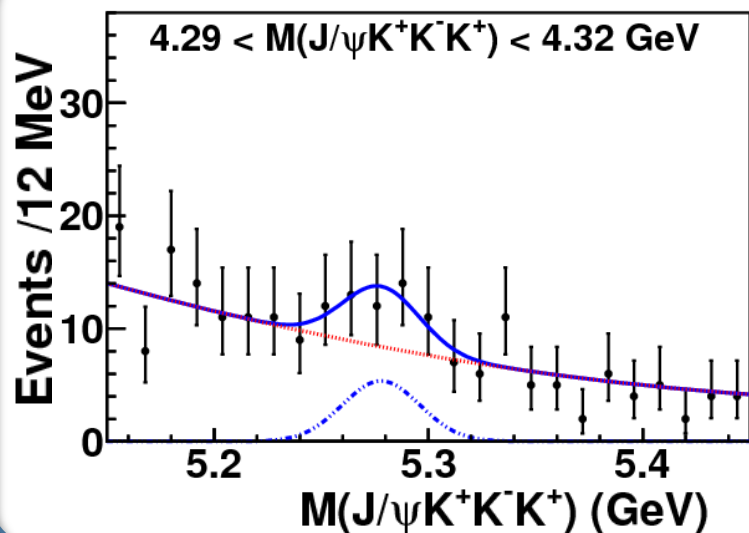
No significant B^+ signal

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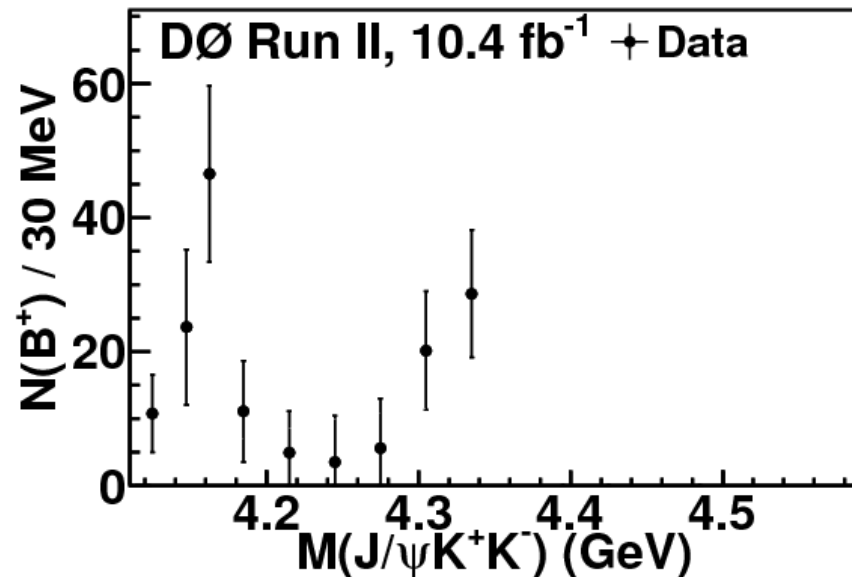
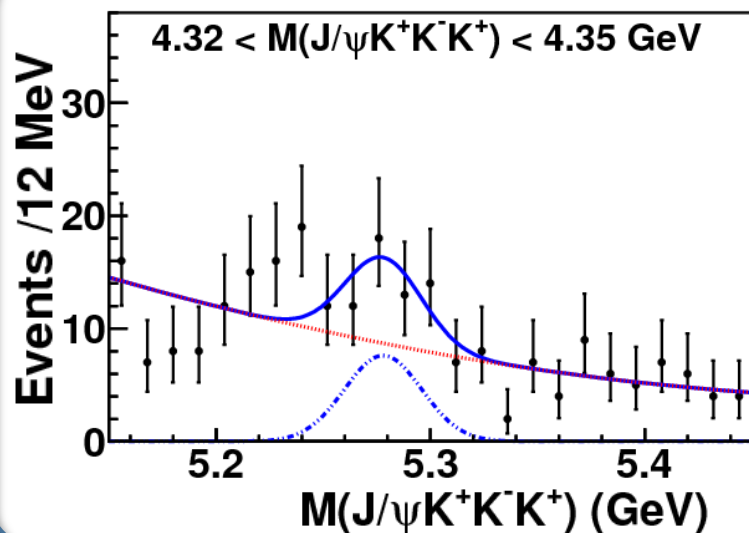
Some small B^+ -like excess

Building $M(J/\psi\phi)$ Distribution



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- 2 of width 15 MeV in $X(4140)$ search region



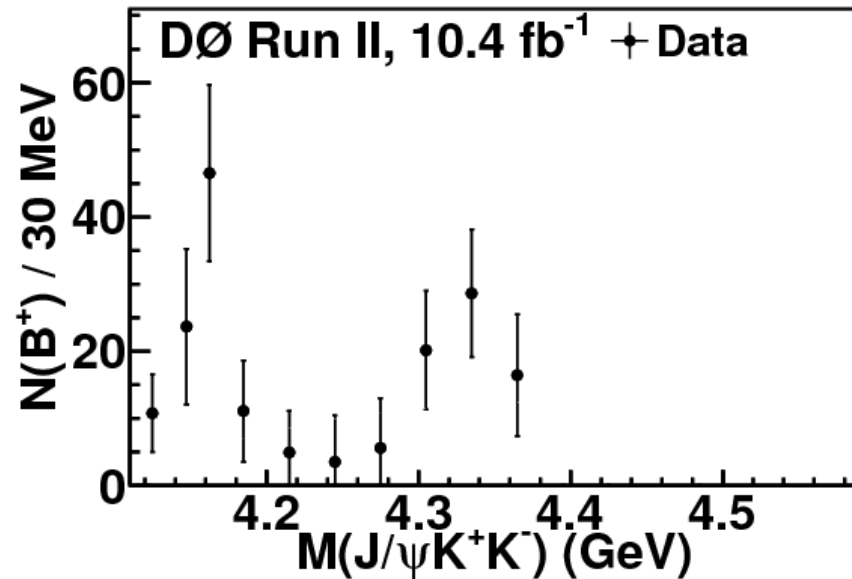
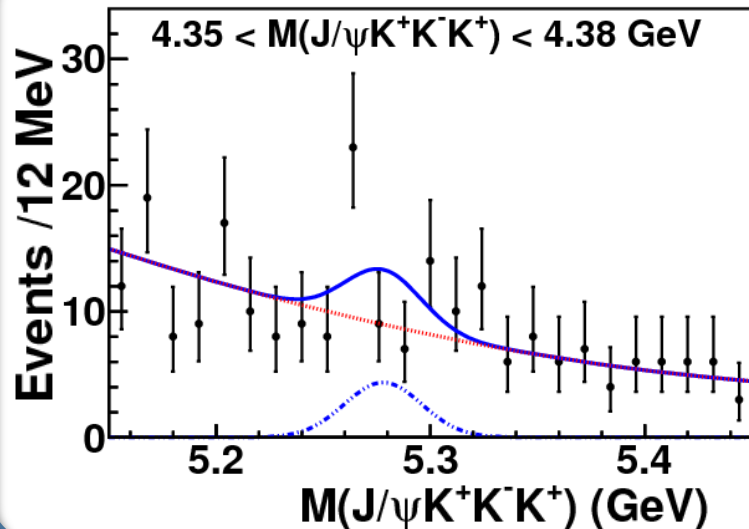
Some small B^+ -like excess

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in $X(4140)$ search region



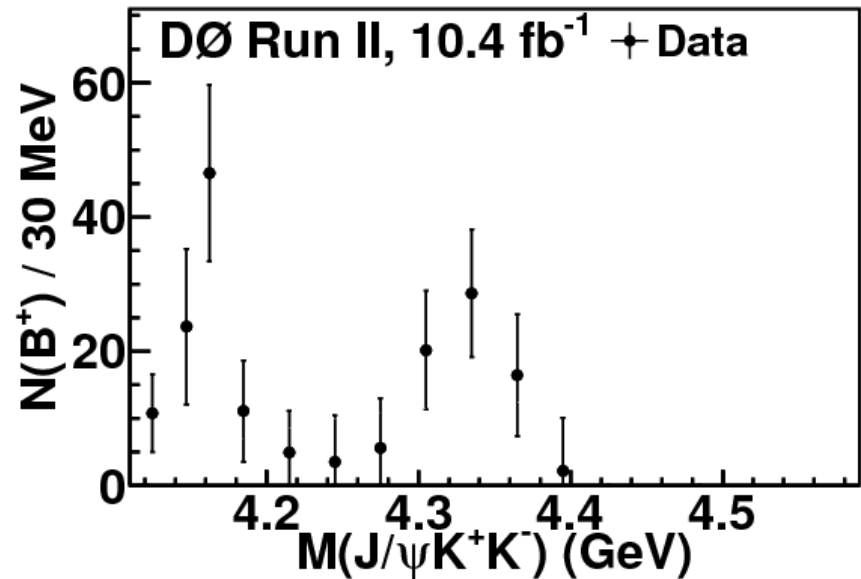
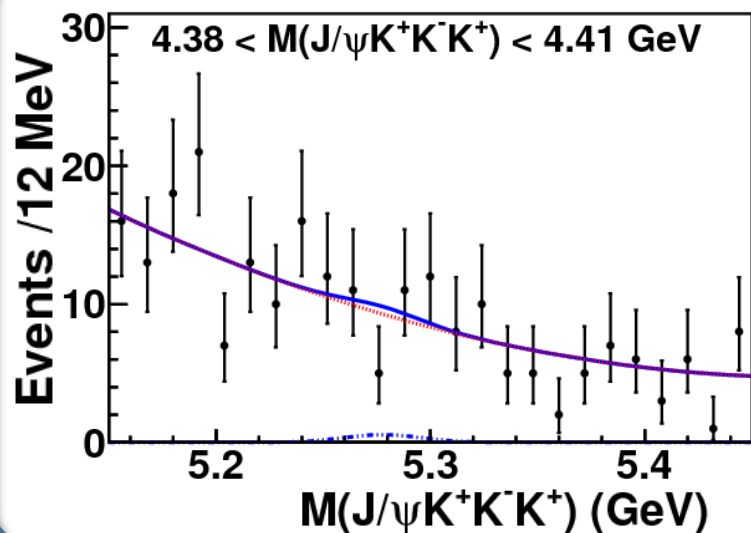
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in $X(4140)$ search region



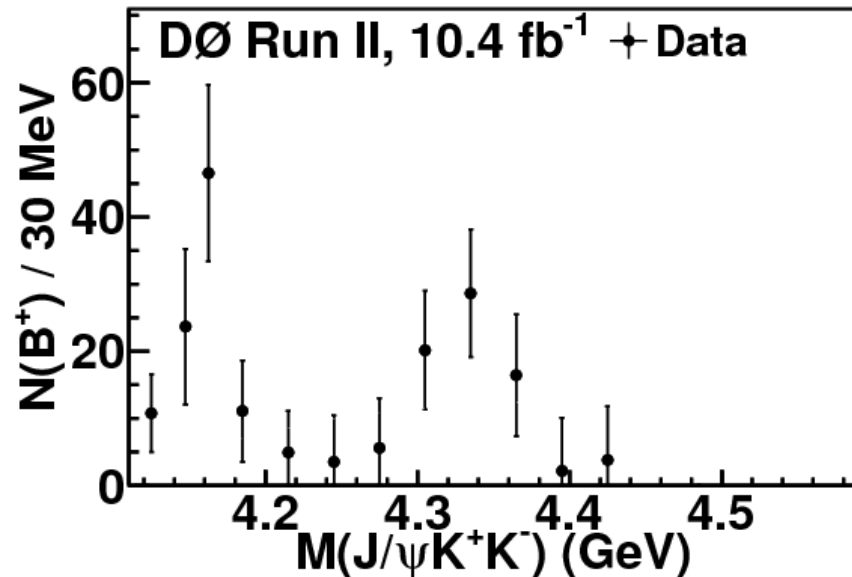
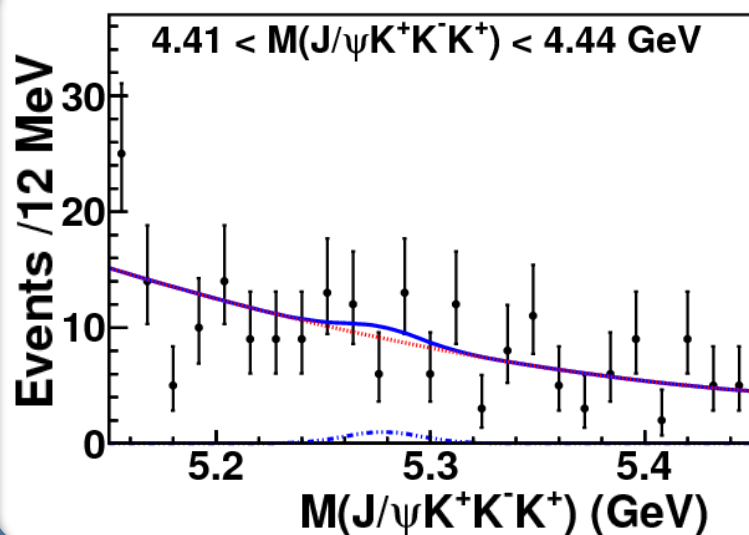
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

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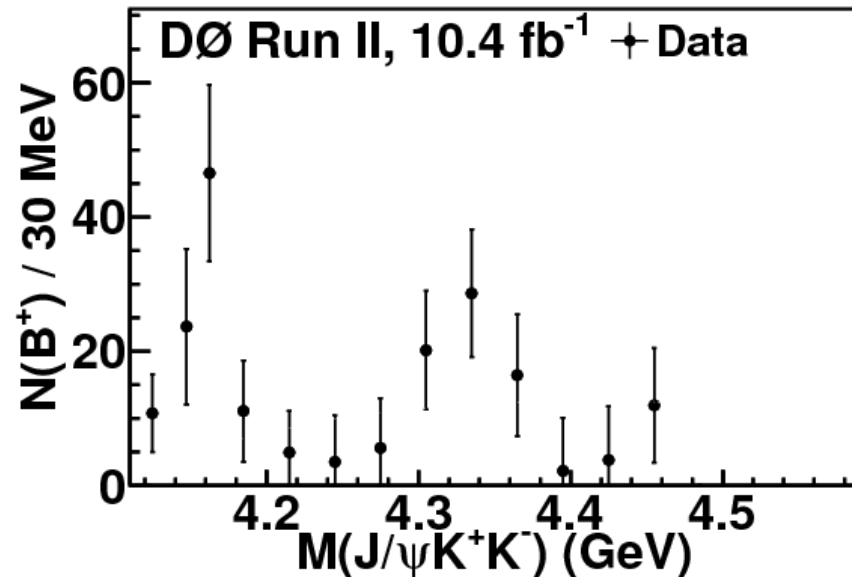
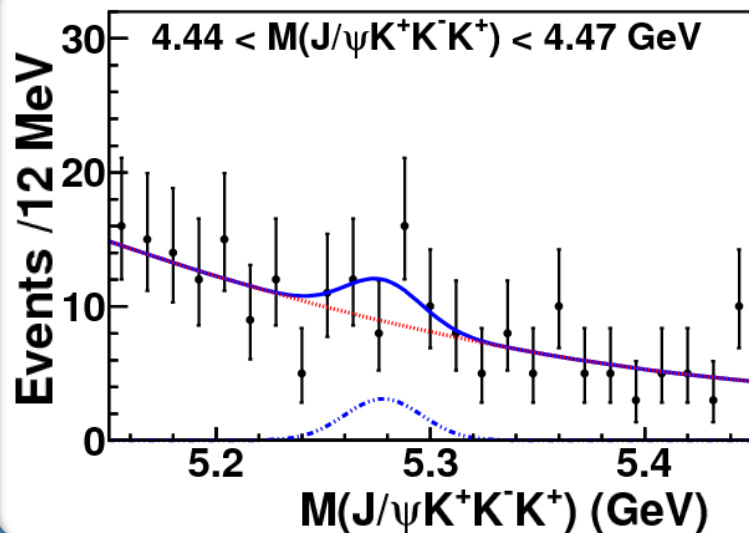
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



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- 2 of width 15 MeV in $X(4140)$ search region



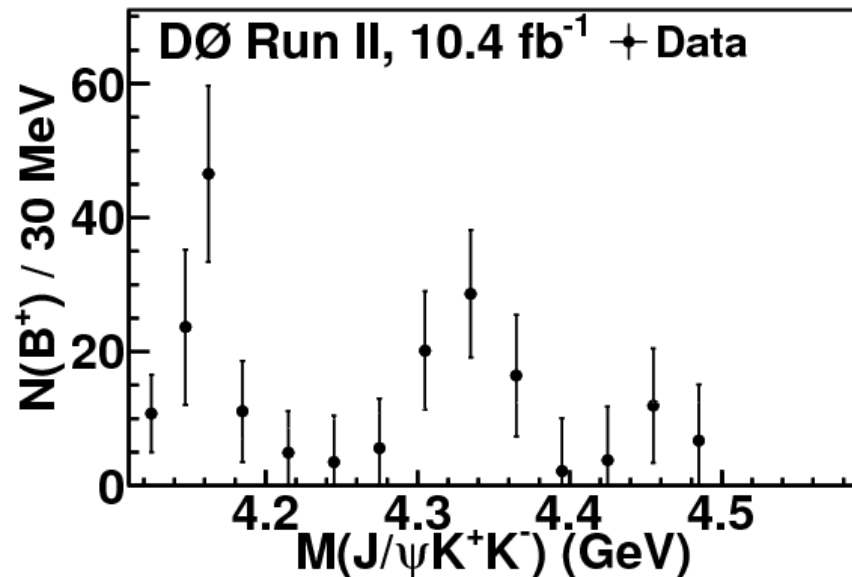
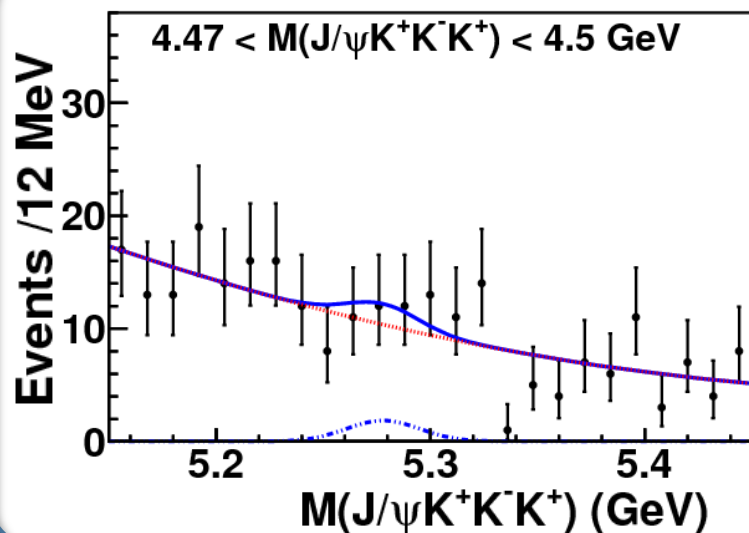
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in $X(4140)$ search region



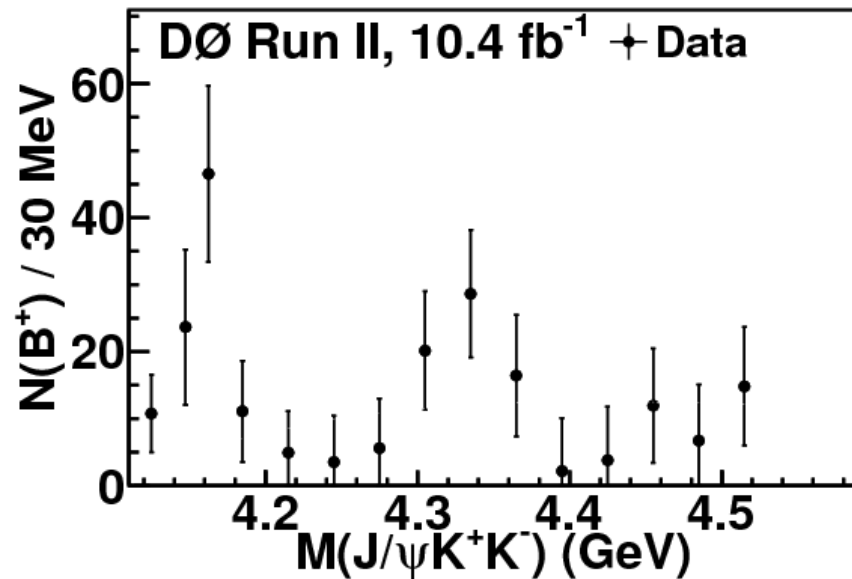
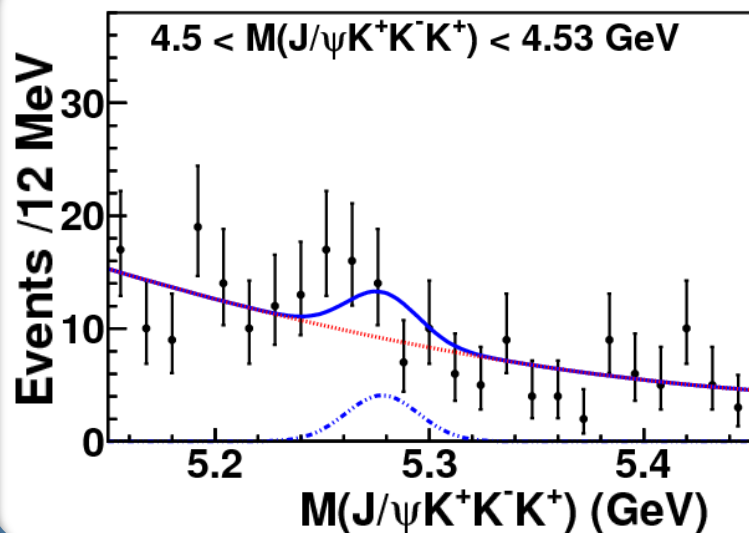
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in $X(4140)$ search region



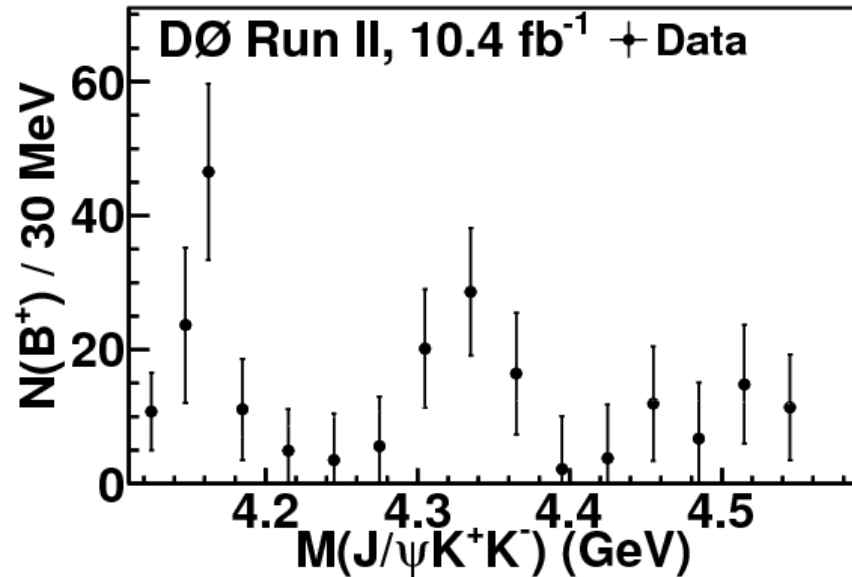
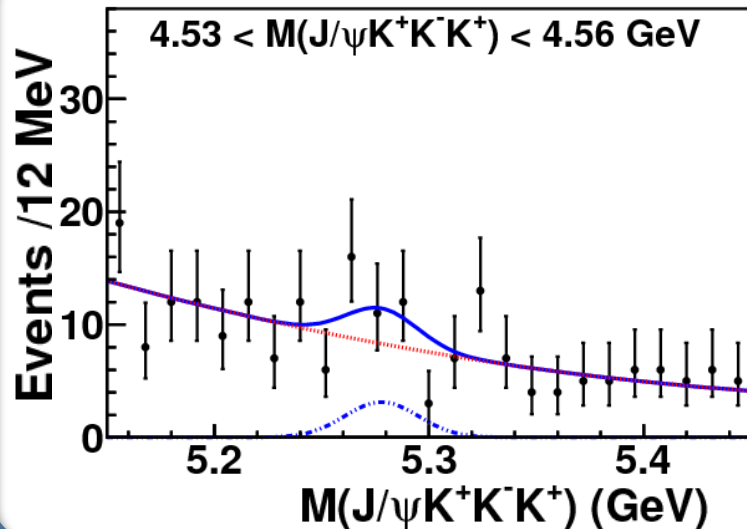
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in $X(4140)$ search region



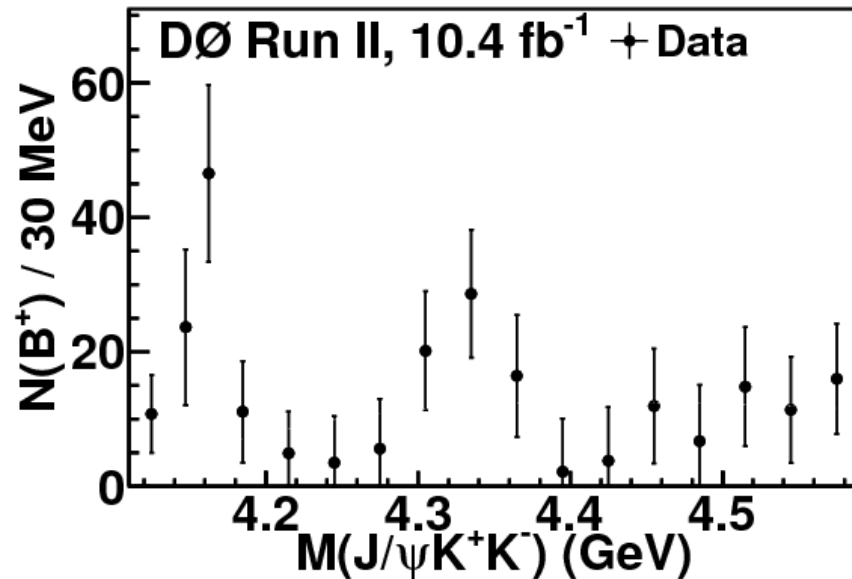
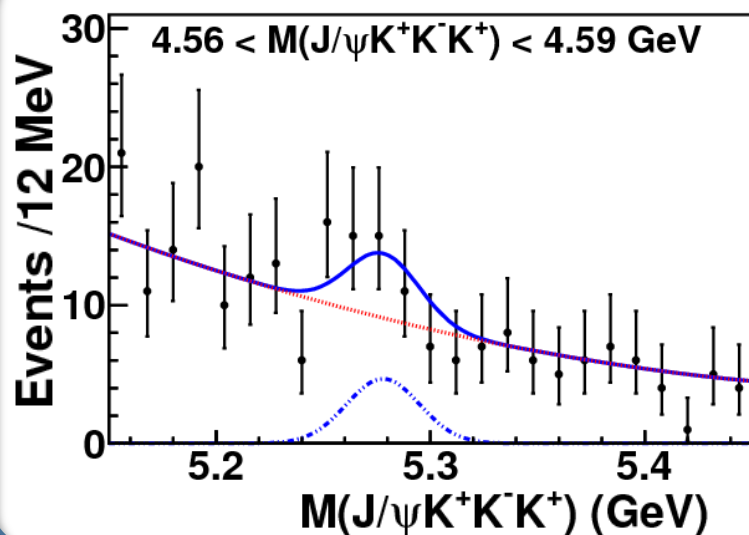
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



17 bins in $M(J/\psi\phi)$:

- 15 of width 30 MeV
- 2 of width 15 MeV in X(4140) search region



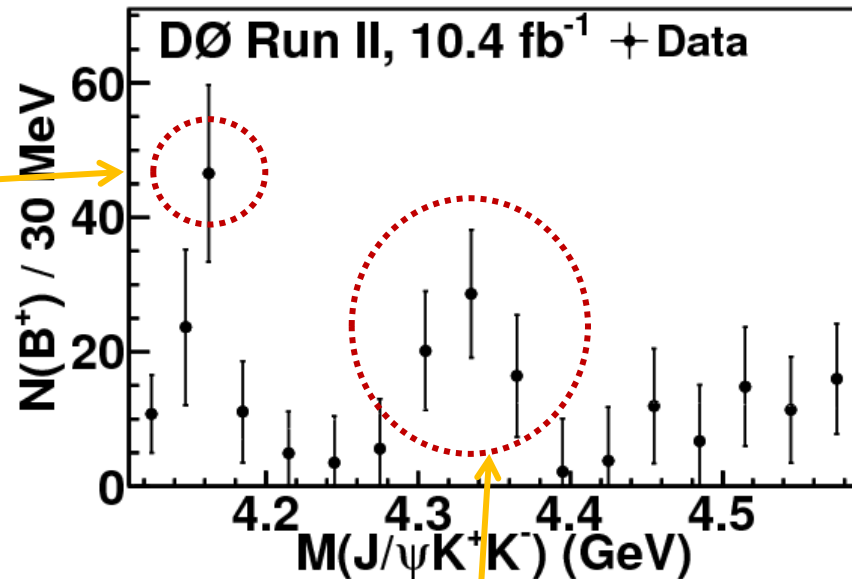
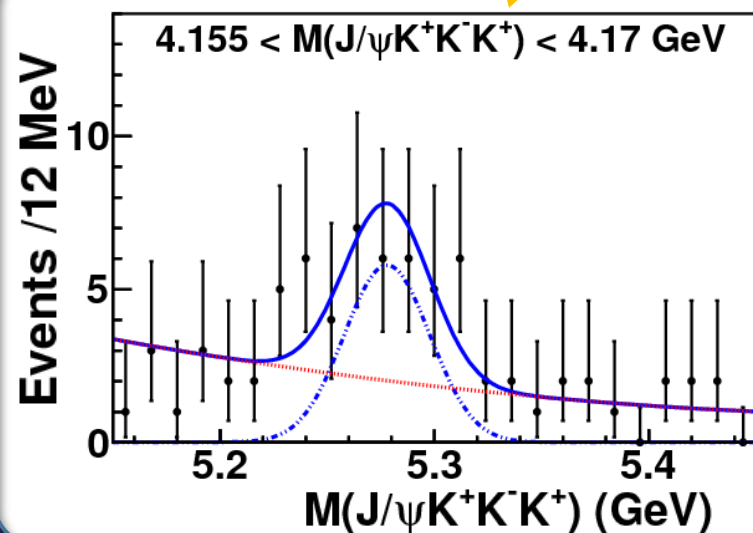
No significant B^+ signal

Building $M(J/\psi\phi)$ Distribution



Clear evidence for peaking structure in $M(J/\psi KK)$ distribution near threshold

We interpret this as $X(4140)$



Smaller excess, over several bins, at larger mass – not statistically significant.

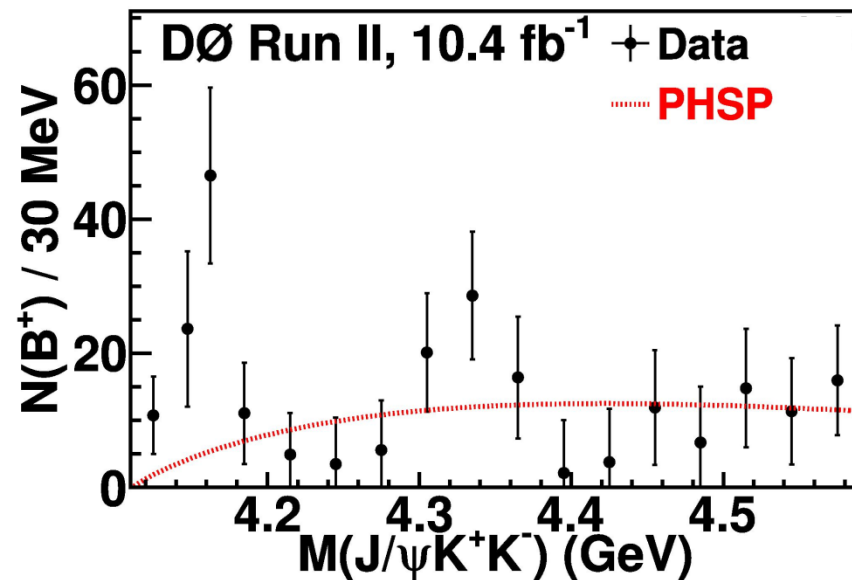
Fit Models



Binned χ^2 fit to data

Background-only fit hypothesis:

Use 3-body phase space model



Fit Models



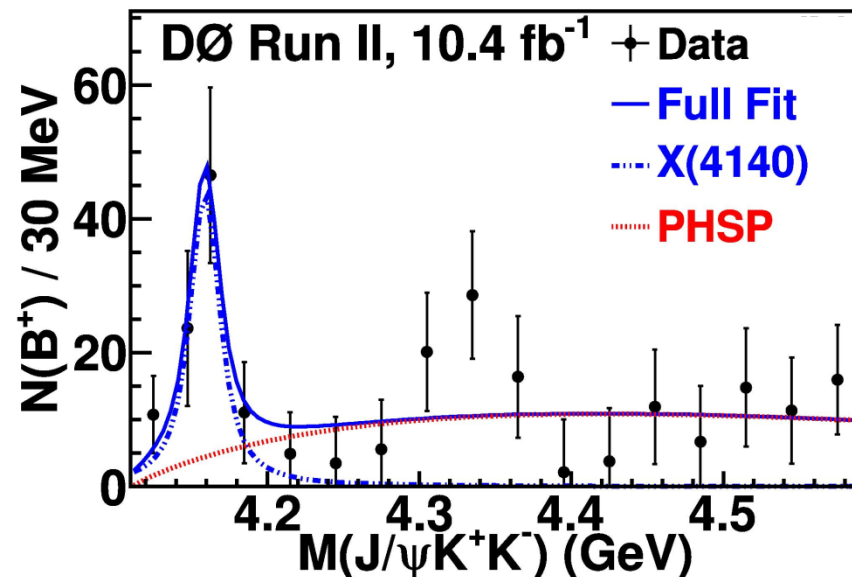
Binned χ^2 fit to data

Background-only fit hypothesis:

Use 3-body phase space model

Now add X(4140) signal component:

- Relativistic Breit-Wigner (free width and mass)
- Convolved with Gaussian resolution of width 4 MeV (fixed from simulation)



Statistical significance:

$$\Delta\chi^2 = 14.7 \text{ for 3 degrees-of-freedom}$$

$$\Rightarrow \mathbf{3.1\sigma}$$

Fit Models



Binned χ^2 fit to data

Background-only fit hypothesis:

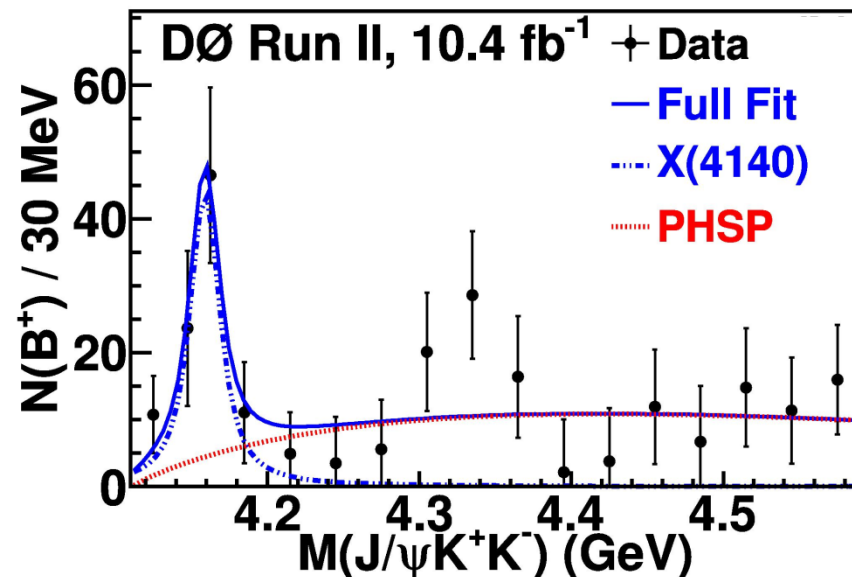
Use 3-body phase space model

Now add X(4140) signal component:

- Relativistic Breit-Wigner (free width and mass)
- Convolved with Gaussian resolution of width 4 MeV (fixed from simulation)

Measure relative branching fraction to X(4140):

$$\Rightarrow \frac{\mathcal{B}[B^+ \rightarrow X(4140)K^+]}{\mathcal{B}[B^+ \rightarrow J/\psi \phi K^+]} = [21 \pm 8 \text{ (stat.)}] \%$$



Fit Models



Binned χ^2 fit to data

Background-only fit hypothesis:

Use 3-body phase space model

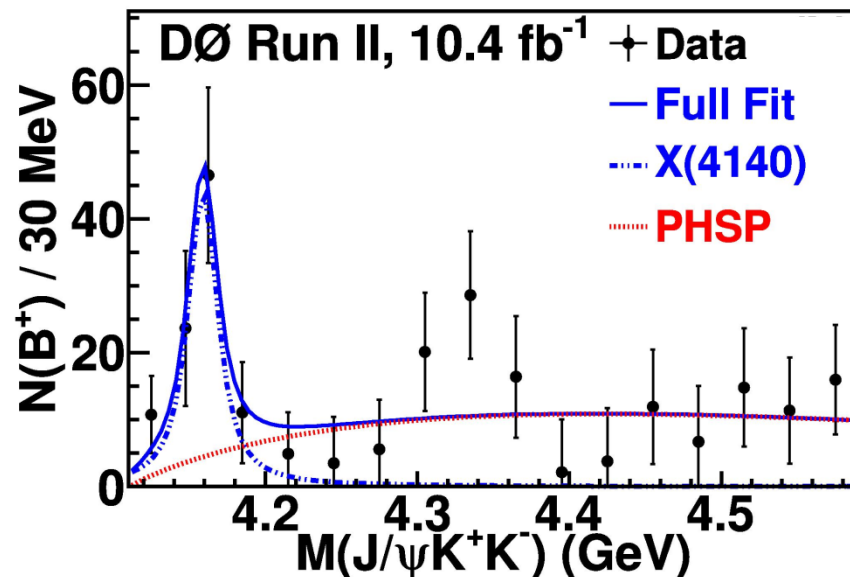
Now add X(4140) signal component:

- Relativistic Breit-Wigner (free width and mass)
- Convolved with Gaussian resolution of width 4 MeV (fixed from simulation)

Mass and width:

$$M[X(4140)] = 4159.0 \pm 4.3 \text{ (stat.) MeV}$$

$$\Gamma[X(4140)] = 19.9 \pm 12.6 \text{ (stat.) MeV}$$



Fit Models



Binned χ^2 fit to data

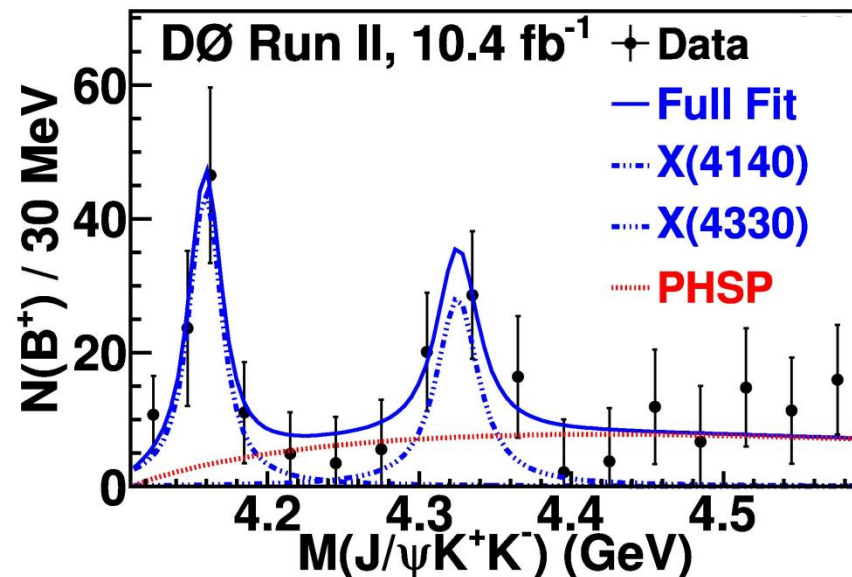
Background-only fit hypothesis:

Use 3-body phase space model

Add contribution from **second peak**:

- Relativistic Breit-Wigner (width fixed at 30 MeV to allow stable fit)
- Convolved with Gaussian resolution of width 4 MeV (fixed from simulation)

Second peak:
<3 σ significance



$$N[X(4330)] = 47 \pm 20 \text{ (stat.) events}$$

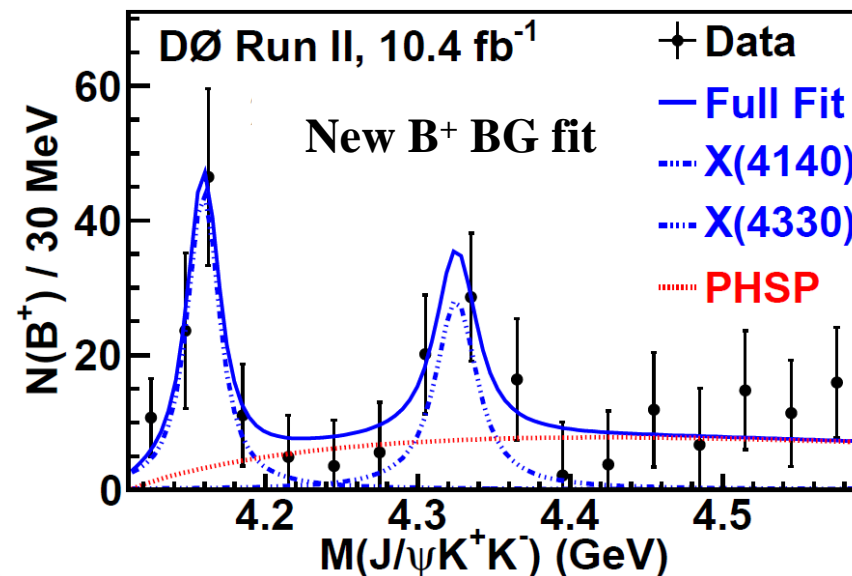
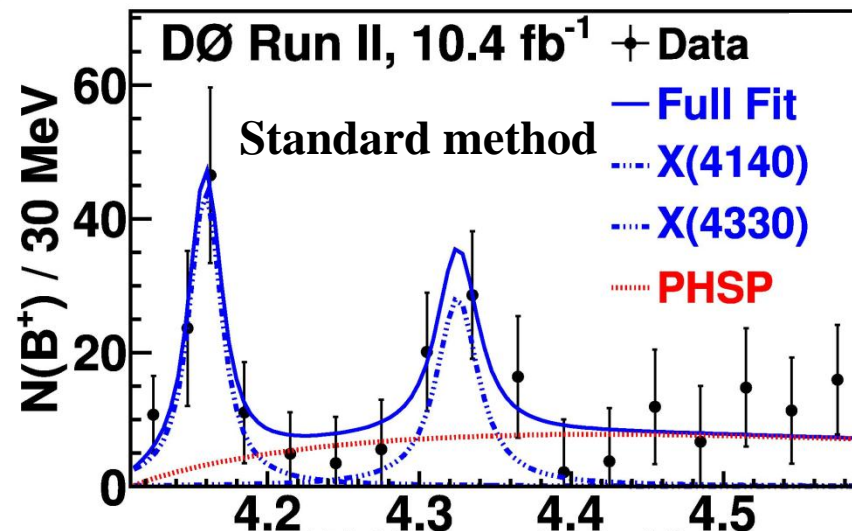
$$M[X(4330)] = 4328.5 \pm 12.0 \text{ (stat.) MeV}$$

Cross-Checks



Test robustness of peak(s) by repeating analysis with different selections / methods.

- 1) Different BG parameterization in B^+ fits ($2^{\text{nd}} \rightarrow 3^{\text{rd}}$ order polynomial)



Cross-Checks

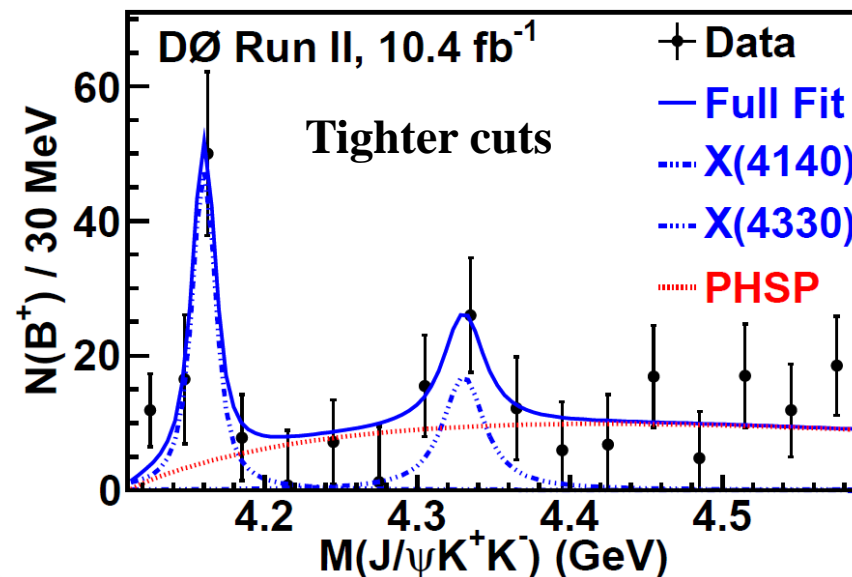
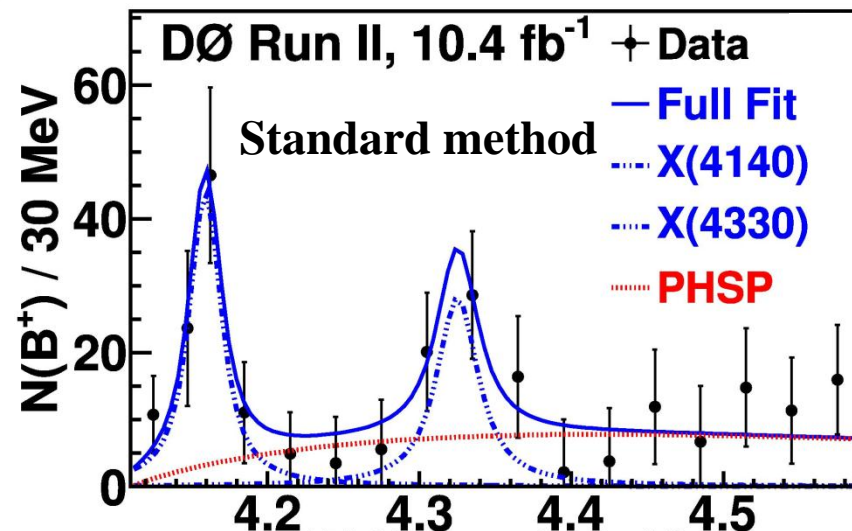


Test robustness of peak(s) by repeating analysis with different selections / methods.

2) Tighter selection cuts

$$\chi^2_{\text{max}}(\text{B}^+ \text{ vertex fit}): 20 \rightarrow 15$$

$$L_{xy}(\text{B}^+) > 250 \mu\text{m} \rightarrow L_{xy}/\sigma(L_{xy}) > 8$$



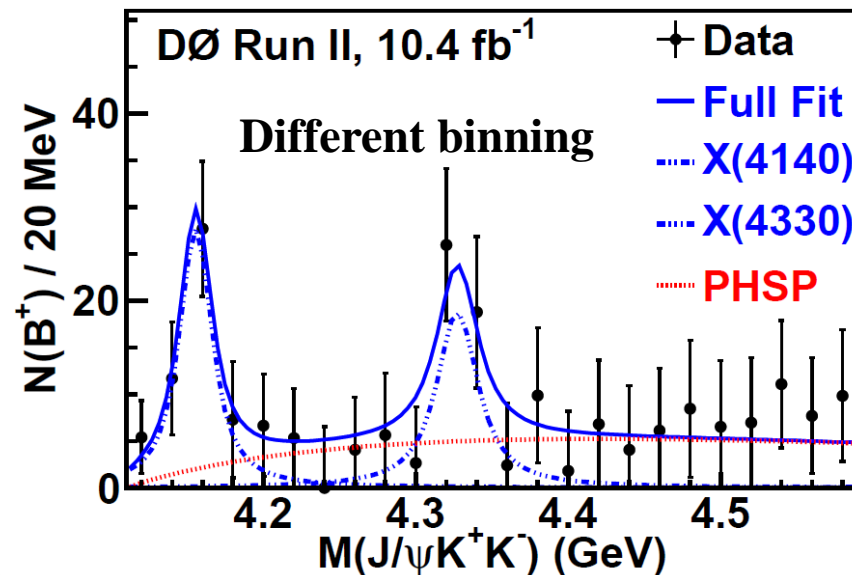
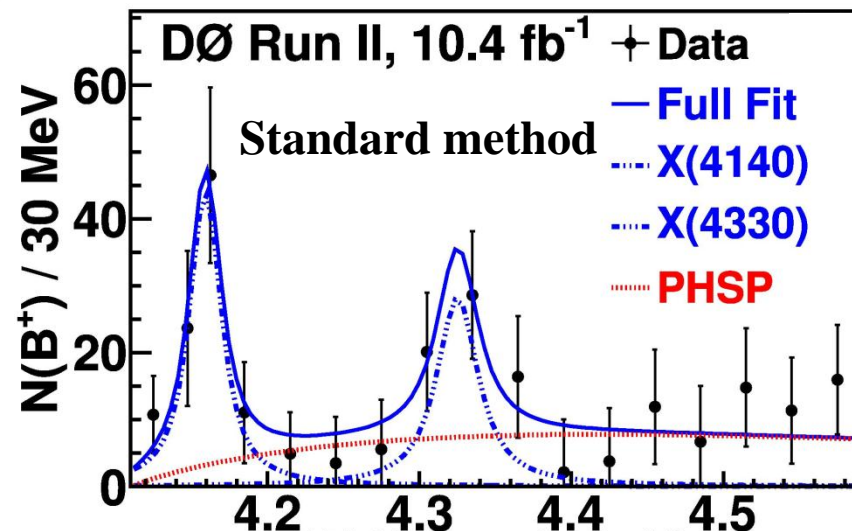
Cross-Checks



Test robustness of peak(s) by repeating analysis with different selections / methods.

3) Smaller $M(J/\psi\phi)$ bins

17 \rightarrow 24 bins



Cross-Checks

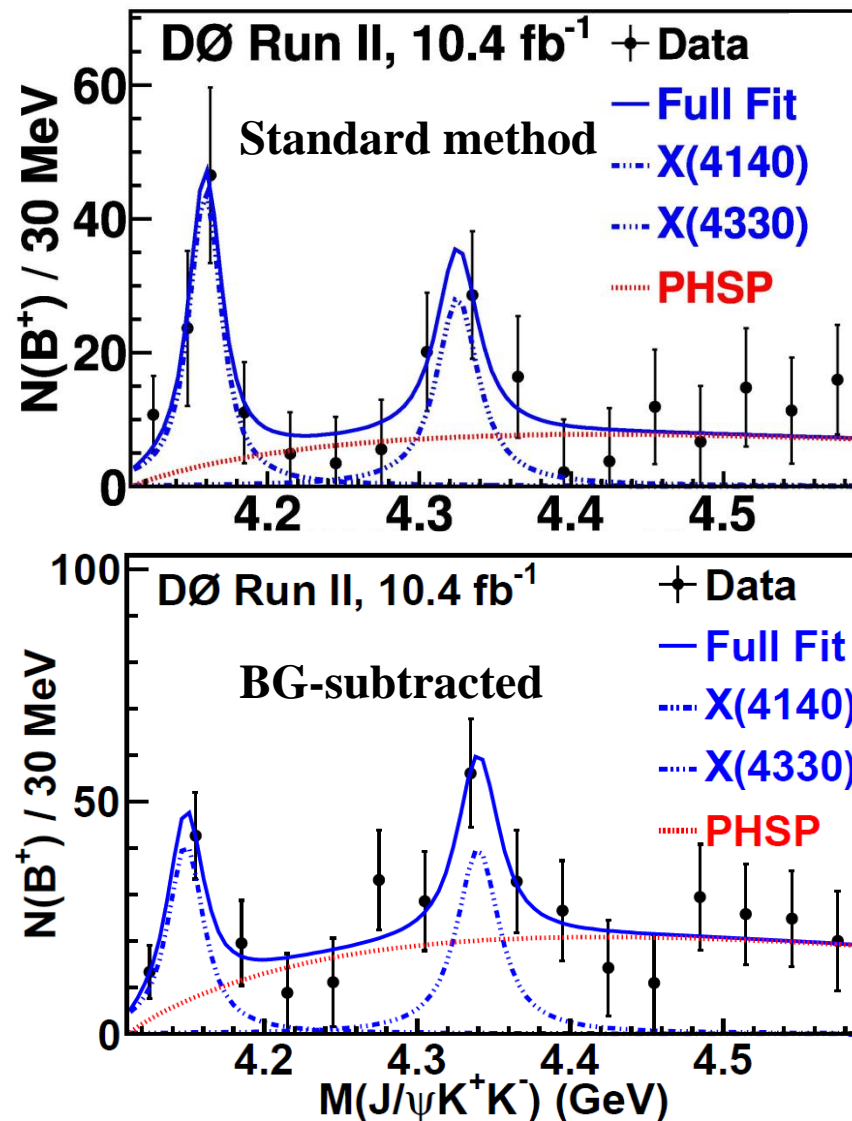


Test robustness of peak(s) by repeating analysis with different selections / methods.

4) Use background-subtracted distribution (“strategy 1”)

In all cases:

- Mass and width of X(4140) are consistent
- Mass of X(4330) consistent
- Statistical significance of X(4140) always $>3\sigma$



Systematic Uncertainties



Reasonable variations of fits are performed to establish systematic uncertainties

1) For the $M(J/\psi\phi K)$ fits to extract the B^+ yield:

- Mean B^+ mass is varied by ± 3 MeV
- B^+ mass resolution is varied by ± 3 MeV
- Background model is varied

Systematic Uncertainties



Reasonable variations of fits are performed to establish systematic uncertainties

1) For the $M(J/\psi\phi K)$ fits to extract the B^+ yield:

- Mean B^+ mass is varied by ± 3 MeV
- B^+ mass resolution is varied by ± 3 MeV
- Background model is varied

2) For the $M(J/\psi\phi)$ fits to determine $X(4140)$ parameters:

- Alternative efficiency corrections: either constant efficiency, or twice the variation observed from MC versus $M(J/\psi\phi)$
- Alternative $J/\psi\phi$ mass resolution: $4 \rightarrow 10$ MeV (only affects $X(4140)$ width)

Systematic Uncertainties



Reasonable variations of fits are performed to establish systematic uncertainties

1) For the $M(J/\psi\phi K)$ fits to extract the B^+ yield:

- Mean B^+ mass is varied by ± 3 MeV
- B^+ mass resolution is varied by ± 3 MeV
- Background model is varied

Mass scale & resolution model tested in-situ using decays:

$$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$$

$$X(3872) \rightarrow J/\psi \pi^+ \pi^-$$

2) For the $M(J/\psi\phi)$ fits to determine $X(4140)$ parameters:

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Final Results



We find evidence at **$>3\sigma$ significance** for the decay:

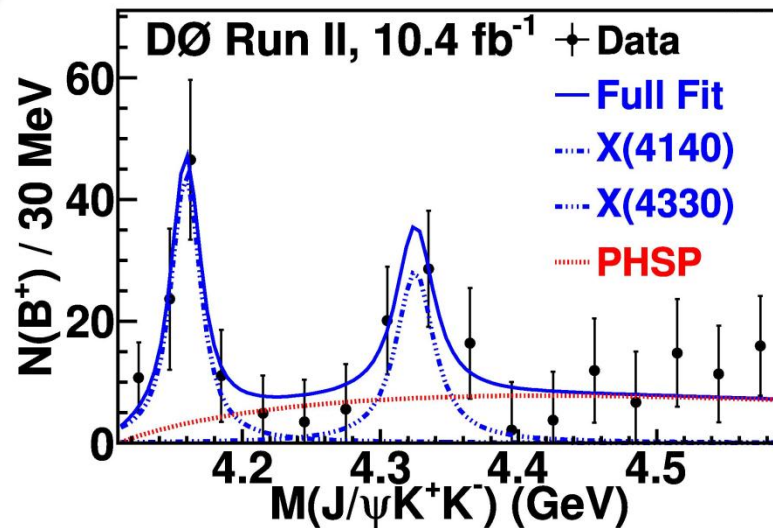
$$B^+ \rightarrow X(4140)K^+, \quad X(4140) \rightarrow J/\psi\phi$$

The mass, width, and relative decay branching fraction are measured to be:

$$\begin{aligned} M[X(4140)] \\ = 4159.0 \pm 4.3 \text{ (stat.)} \pm 6.6 \text{ (syst.) MeV} \end{aligned}$$

$$\begin{aligned} \Gamma[X(4140)] \\ = 19.9 \pm 12.6 \text{ (stat.) } {}^{+1}_{-8} \text{ (syst.) MeV} \end{aligned}$$

$$\frac{\mathcal{B}[B^+ \rightarrow X(4140)K^+]}{\mathcal{B}[B^+ \rightarrow J/\psi\phi K^+]} = [21 \pm 8 \text{ (stat.)} \pm 4 \text{ (syst.)}] \%$$



Final Results



We find evidence at **>3 σ significance** for the decay:

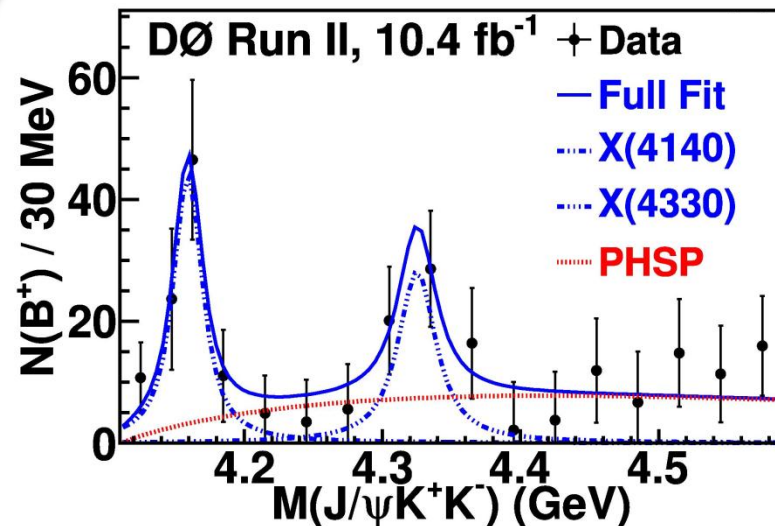
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$$\frac{\mathcal{B}[B^+ \rightarrow X(4140)K^+]}{\mathcal{B}[B^+ \rightarrow J/\psi\phi K^+]} = [21 \pm 8 \text{ (stat.)} \pm 4 \text{ (syst.)}] \%$$



The data also accommodate a second structure with $<3\sigma$ significance at 4328.5 ± 12.0 MeV

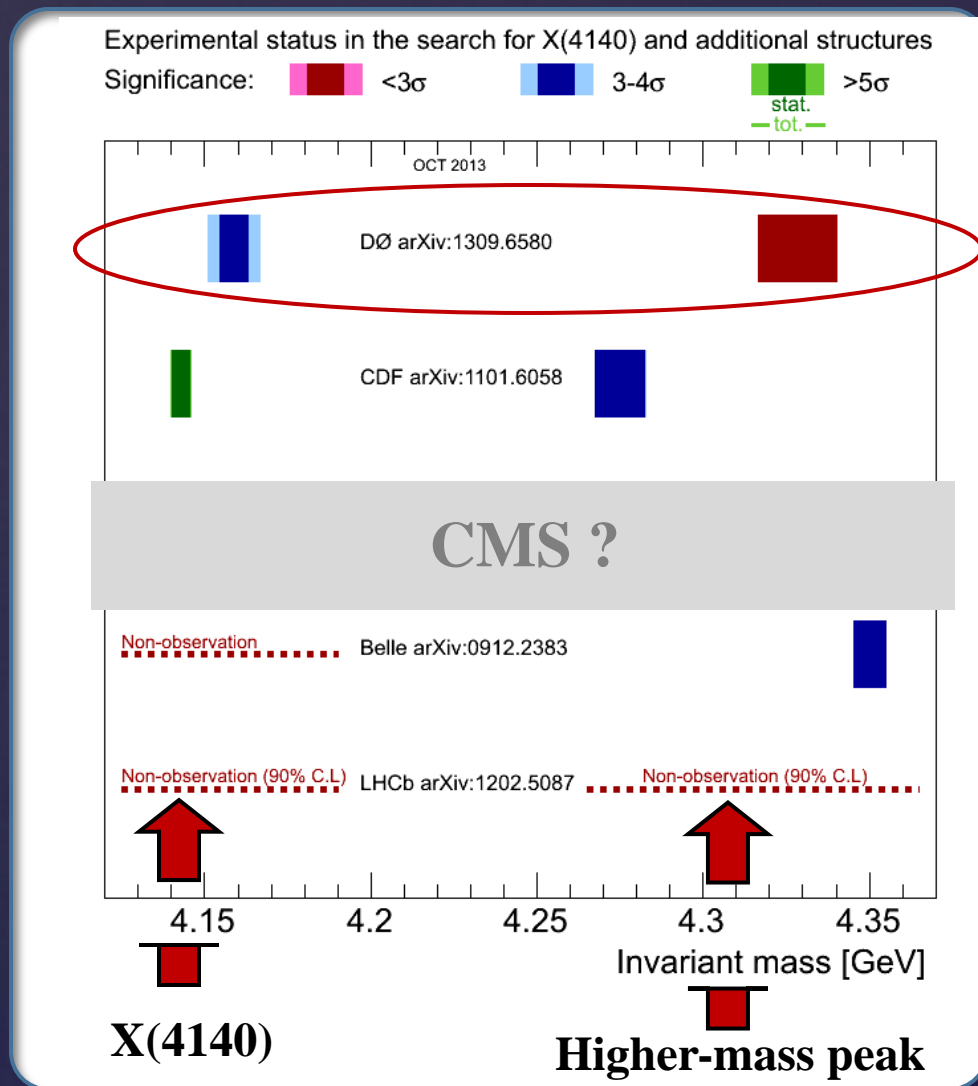
Summary



DØ find **evidence** for narrow resonance near $J/\psi\phi$ threshold

- Mass slightly higher than CDF, consistent within 2σ
- Width consistent with CDF
- Second higher-mass excess inconsistent with CDF, consistent with Belle

Thank-you



Extra Slides

Testing the Mass Scale



Mass scale and resolution is tested in-situ in data using decays:

$$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$$

$$X(3872) \rightarrow J/\psi \pi^+ \pi^-$$



- Measured masses agree with WA values
- Widths are consistent with resolution expected from simulation

Assign systematic uncertainty by comparing nominal mass with alternative definition:

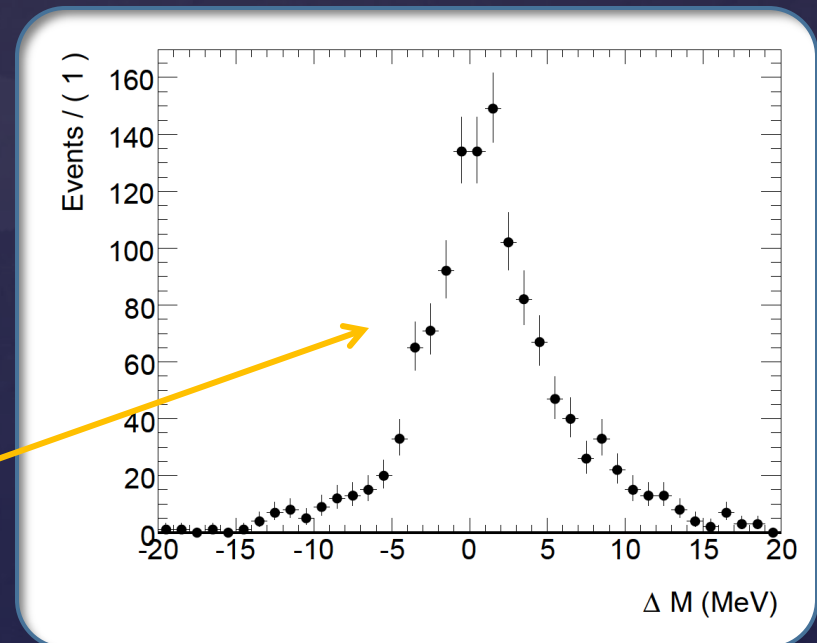
Nominal: Constrain J/ψ mass to PDG value:

$$M(X) = M(J/\psi K K)$$

Alternative:

$$M_{\text{alt}}(X) = M(\mu^+ \mu^- K^+ K^-) - M(\mu^+ \mu^-) + M(J/\psi)$$

$\Delta M = M(X) - M_{\text{alt}}(X)$ centered at zero, with RMS 5.2 MeV assigned as systematic uncertainty



Mass Resolution

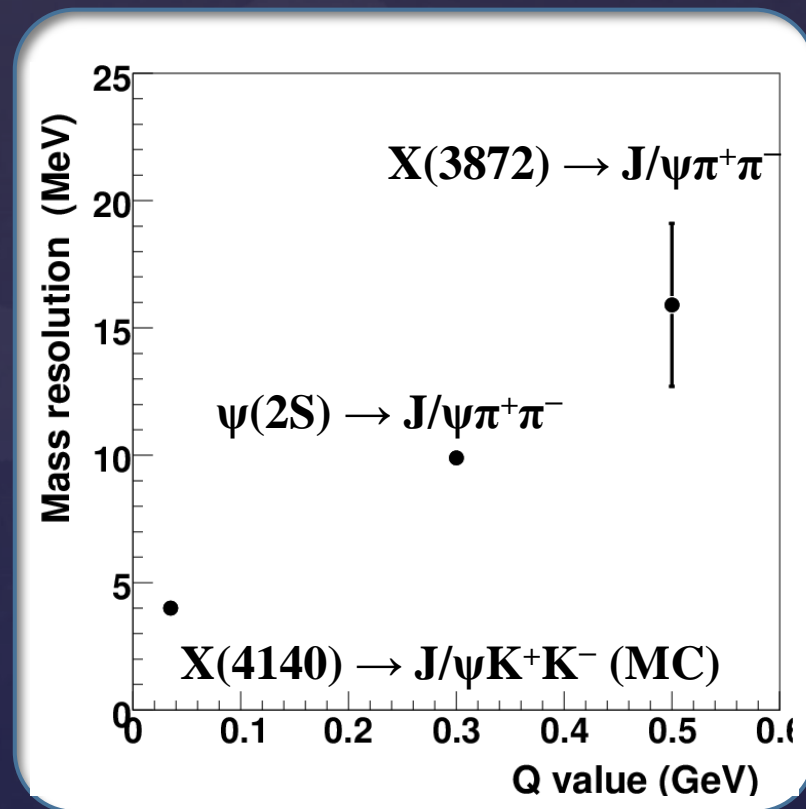


Test $M(J/\psi\phi)$ resolution for $X(4140)$ (from MC) by comparing widths of $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ and $X(3872) \rightarrow J/\psi\pi^+\pi^-$ peaks in data and MC

Default resolution chosen in $X(4140)$ fit is 4 MeV (from MC)

Apply systematic uncertainty by repeating fits with $X(4140)$ set at 10 MeV, i.e. the data-confirmed resolution for the decay $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ (which has a larger Q^2)

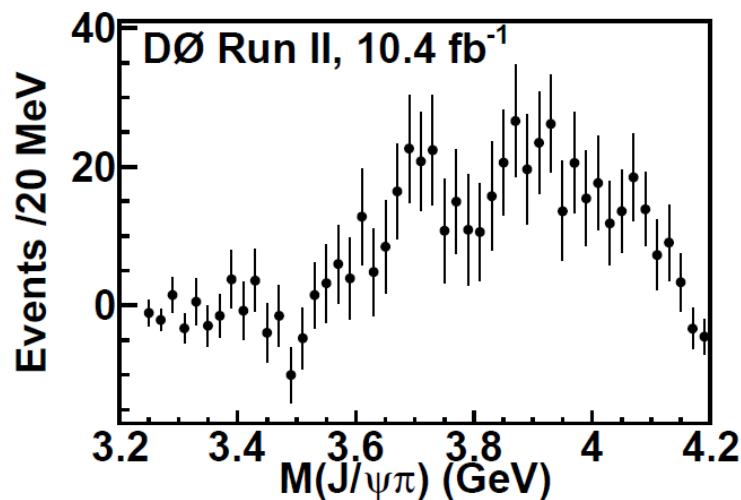
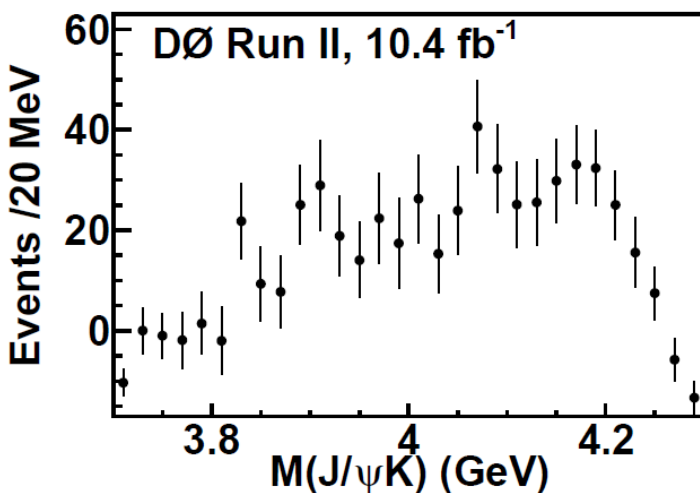
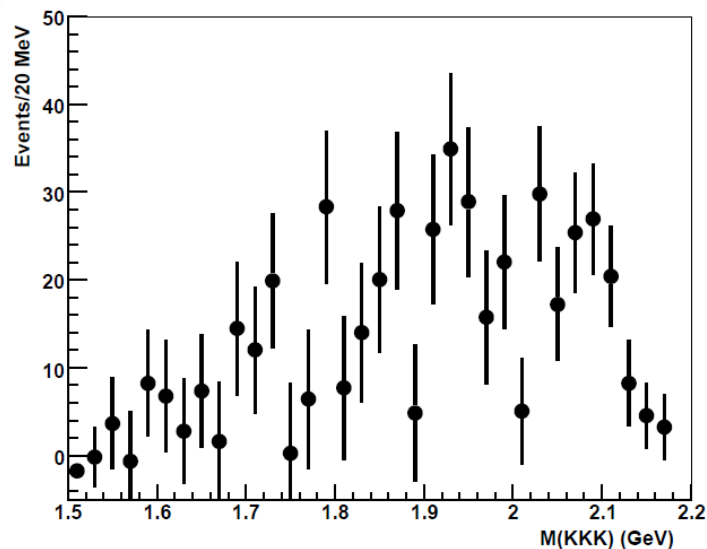
No change in mass or significance, but natural width from fit is slightly reduced.



Peaking Backgrounds

Examine sideband-subtracted $M(KKK)$ distribution to look for additional peaking backgrounds:

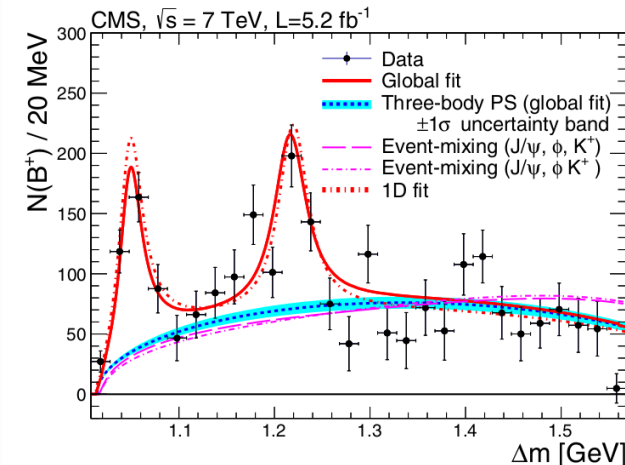
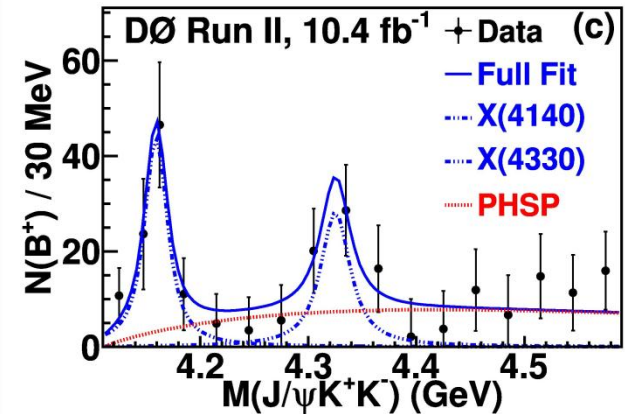
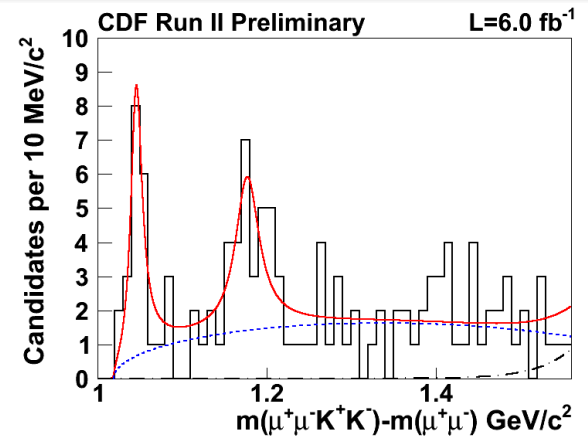
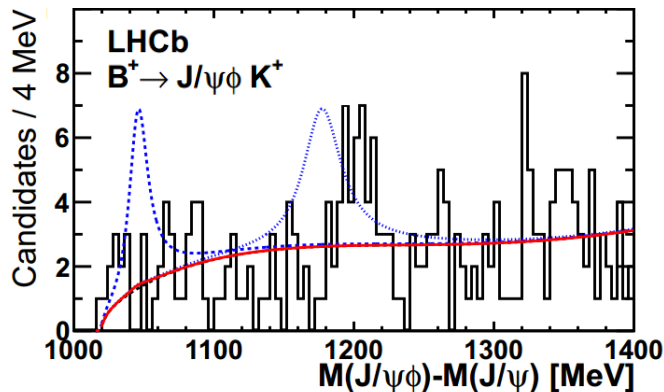
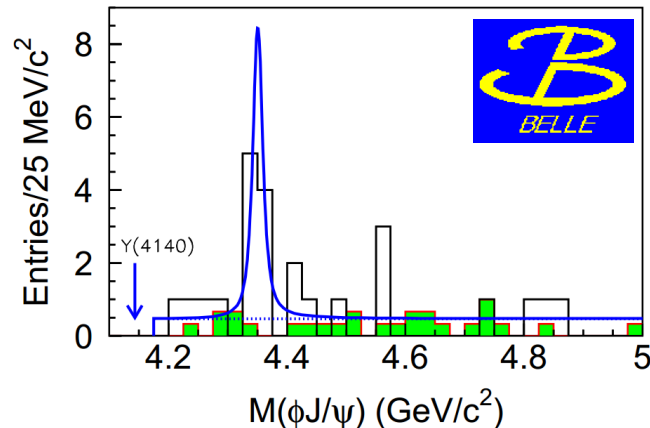
Repeat searches for intermediate $J/\psi \pi^\pm(K^\pm)$ resonances, with background contributions removed by sideband subtraction.



Global Comparison

CDF, CMS, D0 all see excess consistent with X(4140)

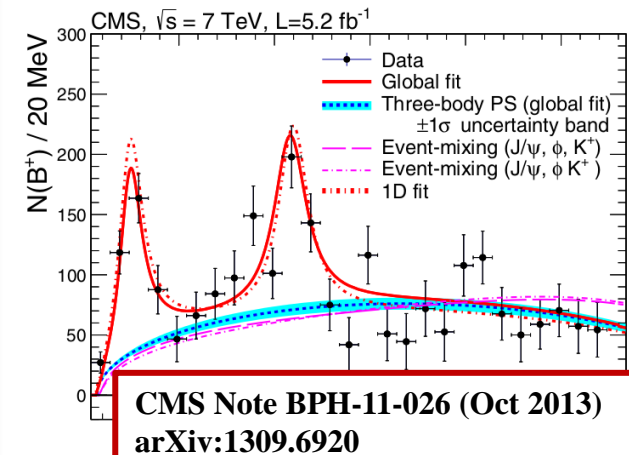
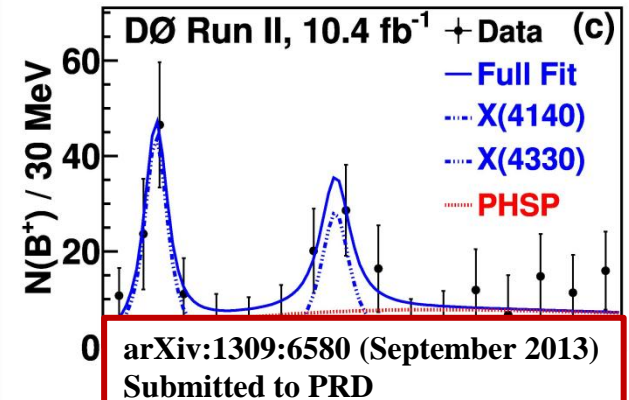
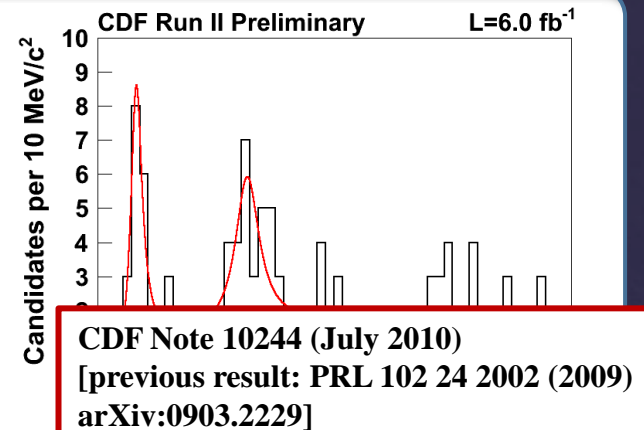
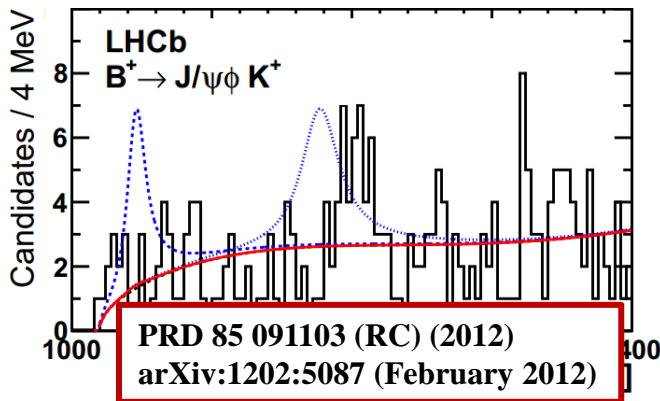
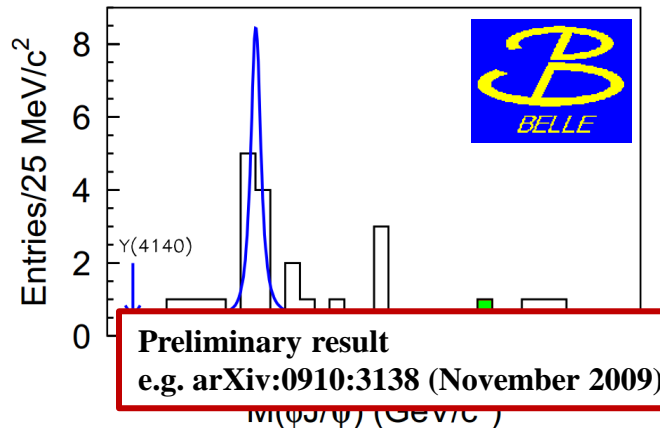
Belle, LHCb see nothing (LHCb set limit)



Global Comparison

CDF, CMS, D0 all see excess consistent with X(4140)

Belle, LHCb see nothing (LHCb set limit)



Combinations

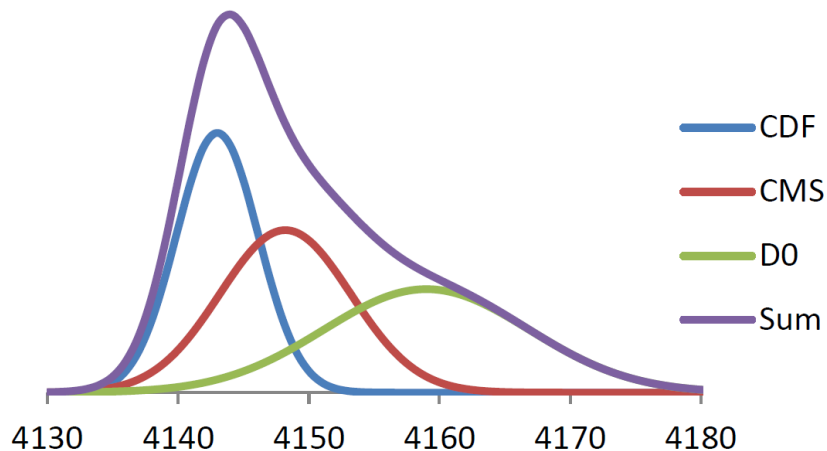
Simple combination of search results:

$X(4140)$:

Mean mass: $4146 \pm 8 \text{ MeV}$

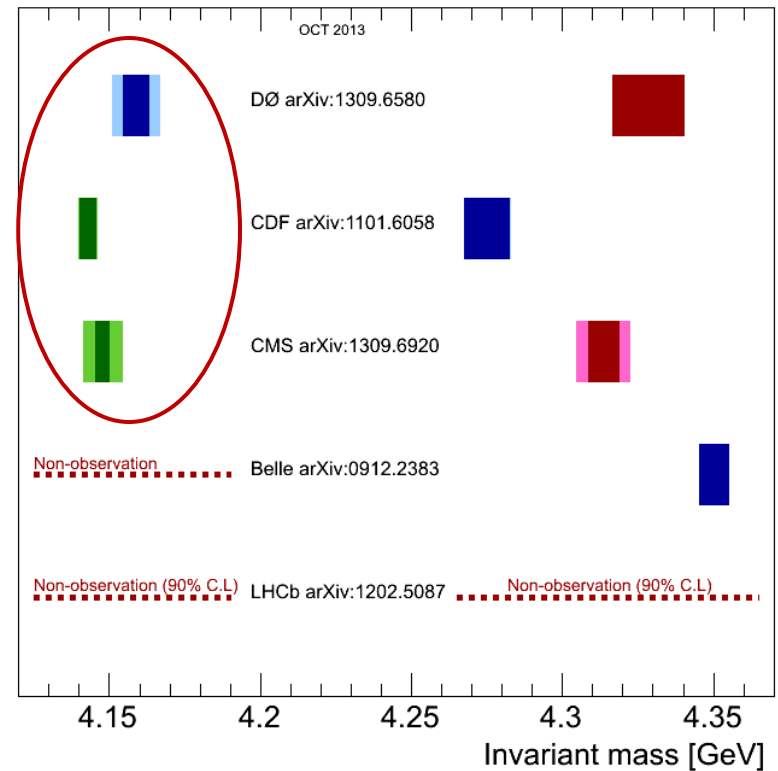
χ^2 of combination: $3.8/2$

p -value: 0.15



Experimental status in the search for $X(4140)$ and additional structures

Significance: ■ $<3\sigma$ ■ $3-4\sigma$ ■ $>5\sigma$



Combinations

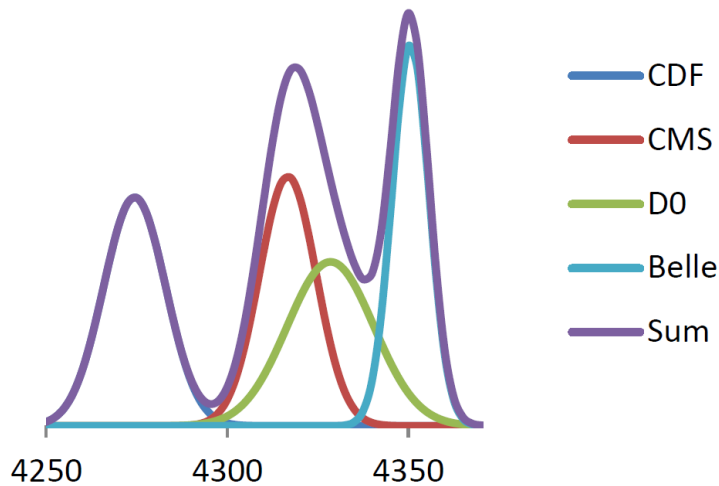
Simple combination of search results:

Higher-mass peak:

Mean mass: 4327 ± 4 MeV

χ^2 of combination: **60/3**

p -value: **< 0.0001**



Experimental status in the search for X(4140) and additional structures

Significance: ■ <3 σ ■ 3-4 σ ■ >5 σ

